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On the possible identity of Nova Geminorum with a small star photographed before the outburst. By H. H. Turner, D.Sc., F.R.S., Savilian Professor.

1. Soon after the announcement of the discovery of Nova *Geminorum*, I heard from Dr. Max Wolf, of Heidelberg, that he had taken a photograph of the region of the Nova on 1903 February 16. This plate is reproduced in *Monthly Notices*, vol. lxiii. plate 13 (opposite p. 330), though by an oversight the letters N and S, E and W, have been transposed; and Dr. Max Wolf remarked, "There is nothing exactly at the place of the Nova, but extremely near to it is a star-like object of about the sixteenth magnitude, and this extends over the place of the Nova, so that the Nova may be a part of this chain-like object."

Dr. Max Wolf kindly sent an enlargement of this negative to the University Observatory, Oxford, and we have measured the position of this object with reference to the stars immediately surrounding it, which have been connected with the Nova micrometrically by Professor Barnard, and also measured here on a plate of 100 min. exposure taken by Mr. Bellamy on April 22.

2. Later we heard that Mr. Parkhurst at the Yerkes Observatory had also photographed the region on February 21 with the 24-inch reflector and an exposure of twenty minutes, showing stars to the 15th or 16th magnitude. The purpose of the photograph was to obtain the region round *X Geminorum*, a variable discovered by Dr. Anderson. The position for 1900·0 of

	R.A.	Decl.
	h m s	° ′
X Geminorum is	6 40 43	+30 23·0
Nova *Geminorum*	6 37 49	+30 2·5

so that the stars near the latter are at the edge of Mr. Parkhurst's plate, and the images are fan-shaped. A positive copy of this plate was kindly sent by Mr. Parkhurst and received at Oxford on June 6. Measures of the same stars have been made on this positive, and also on a negative made from it.

3. The general result of all the measures is not favourable to the supposition that the faint star previously photographed is identical with the Nova, though it does not seem possible to decide the matter conclusively.

4. The stars near the Nova may be conveniently designated by the numbers assigned by Professor E. E. Barnard on p. 5 of *Bulletin* No. 19 of the Yerkes Observatory. His measures have been reduced to "Standard Co-ordinates" (with the Nova as centre) so that they may be compared more readily with measures on photographic plates. For a reason which will presently appear small constants (viz. those entered for n) have been added to all these co-ordinates to reduce them to the mean of the four stars 1, 4, 5, 6. These stars form an irregular quadrilateral enclosing the region of the Nova (n) and the stars 2 and 3; and any systematic errors for stars within this area ought to be smaller than those for the boundary. The columns headed "Oxford" give the differences from Barnard's results of Mr. Bellamy's measures on a plate of 100 min. exposure taken on April 22.

The unit is one réseau interval of 5′ or 300″.

TABLE I.

Standard Co-ordinates of Barnard's Stars and the corrections indicated by Oxford measures.

Star's No.	Barnard.		Oxford.	
	x	y	Δx	Δy
1	+·1332	−·0918	+·0004	·0000
4	−·0493	−·3371	+·0017	+·0017
6	+·1286	+·2637	−·0004	−·0020
5	−·2124	+·1653	−·0009	·0000
2	+·0577	−·2137	+·0021	+·0007
3	−·0303	+·1113	+·0061	−·0017
n	+·0285	−·0644	+·0027	−·0030

5. It will be seen that the agreement for the stars 2, 3, n (the Nova) is not very good, especially in the x co-ordinate. The differences cannot well be due to orientation or scale value, for they would show most in the outer stars. A source of error which has gradually been forced on our attention—what Kapteyn calls the "error of guiding"—seems also inadmissible here, since it produces an effect which increases systematically with the magnitude; and though the stars 2 and 3 are all fainter than 1, 4, 5, 6, and their positive Δx might be due to an "error of guid-

ing," the Nova is of course much brighter and should have a negative residual on this supposition. It seems difficult to account for these errors except as accidental; and, if this is the true view of them, it is worth noting before we pass to the other photographs which have defects from which the Oxford plates ought to be free; viz. they are on a smaller scale, and in the case of Mr. Parkhurst's photograph the images are near the edge of the plate and consequently fan-shaped.

6. Dr. Max Wolf's enlargement was measured both by Mr. Bellamy and myself on April 20, being placed film to film with a réseau for the purpose of measurement. For scale value and orientation five stars were measured, surrounding the region of the Nova and at some distance from it; and it was inferred that measures (x_w, y_w) on the Max Wolf plate were connected with standard co-ordinates (ξ, η) by the approximate formulæ

$$\xi = 0{\cdot}800\ x_w - {\cdot}011\ y_w + \text{const.}$$
$$\eta = 0{\cdot}800\ y_w + {\cdot}011\ x_w + \text{const.}$$

7. It was considered that these coefficients were probably sufficiently exact for application over the small region under examination, the constants being determined from the four stars 1, 4, 5, 6. The images on the enlargement were of very irregular shape, and a more exact determination of the coefficients and constants would require an elaborate discussion of the plate. It may be ultimately necessary to undertake this, but the present preliminary inquiry will at any rate suffice to indicate the limits of possible uncertainty.

8. The Parkhurst plate was measured by Mr. B. Gray and myself on June 11, being first copied on to a plate with a réseau on it. Measures of four stars in different parts of the plate gave for the approximate constants of reduction

$$\xi = -1{\cdot}462\ x_p - {\cdot}0092\ y_p + \text{const.}$$
$$\eta = -1{\cdot}462\ y_p + {\cdot}0092\ x_p + \text{const.}$$

but if these formulæ are applied to the whole plate, the residuals for different stars vary considerably. For the region of the Nova, the co-ordinates of which are about $x_p = 15{\cdot}7$ $y_p = 9{\cdot}6$, the constants differ by about $+\ 0{\cdot}030$ in ξ and $+{\cdot}010$ in η from those deduced from the four reference stars, the co-ordinates of which are (10·7, 4·0) (14·2, 2·4) (14·1, 11·2) (11·5, 10·4). It will be seen that these are all on one side of the Nova, which is too near the edge of the plate to allow of reference stars on the other side. It is more than ever necessary to determine the constants from the stars 1, 4, 5, 6, which surround the region under consideration. Mr. Plummer has tried to find some satisfactory method of dealing with plates taken with reflectors, but without much success; perhaps we may hope for better success in the future; but meanwhile we must fall back on the expedient before used,

of trusting an approximate scale value and orientation over the small area, and determining the constants from the four corner stars.

9. I proceed to give the "Corrections to Barnard" indicated by the three photographs. It seems useless to go further than ·001 of a réseau interval, in view of the great uncertainties of the measures. The objects which might be the Nova on the first two plates have been referred to Barnard's position of the Nova as given in Table I.

TABLE II.

Star's No.	Max Wolf, Feb. 16.		Parkhurst, Feb. 19.		Oxford.	
	Δx	Δy	Δx	Δy	Δx	Δy
1	+·001	−·005	−·002	+·001	·000	·000
4	−·005	+·002	+·002	+·003	+·002	+·002
6	+·001	+·004	·000	−·002	−·001	− 002
5	+·002	−·002	·000	—·002	−·001	·000
2	−·001	+·013	−·002	−·001	+·002	+ 001
3	−·015	−·002	−·006	−·005	+·006	−·002
n	−·016	−·009	−·021	+·005	+·003	−·003
n'	−·070	−·012	—	—	—	—

10. These figures give us some idea of the limits of error. Star 2 has a residual of +·013 or +4″ in y, which is not supported either by the Parkhurst or the Oxford plate, and must be regarded as accidental. The Max Wolf plate has been magnified five times, and the images are large and irregular. The x measures for star 3 are somewhat remarkable. Both plates taken before the outburst indicate a negative correction to Barnard's measures of March 30, and the Oxford plate, taken on April 22, shows a distinctly positive correction. The figures would be suited by the supposition of a very rapid proper motion (20″ a year say), but this supposition is scarcely admissible, at any rate without further evidence. I wrote to Professor Barnard, hoping that he might have measures on different nights which would give some information. The measures he made were as follows :

Nova and Star 3.

1903 March 30	341°·61	55″·69
April 27	341°·45	(too difficult)

Since a P.M. in R.A. would largely affect the position-angle, these measures are good evidence against any exceptional proper motion.

11. We now come to the question whether the Nova is identical with the small star near its place. The place of the Nova itself seems to be satisfactory, the Oxford measures being in fair agreement with Professor Barnard's. On the Max Wolf plate the image near the place of the Nova is double ; in the letter quoted in the first paragraph it is called a "chain-like object." The Parkhurst plate does not support the view that there is a double star at this place, and the double appearance is probably a photographic defect. If it is an elongated image of a single star, we should take some sort of a mean between the positions given for the two condensations n and n' ; but the most favourable supposition for identity with the Nova is clearly that n' is spurious, and n is the true image of the star shown on the Parkhurst plate. Even then it differs from the Parkhurst object by ·014 or 4″ in y, in the opposite direction to the difference for star 2. In the light of these discordances, are we to regard the differences from Barnard in the x co-ordinate as merely accidental ? If the Max Wolf plate had stood alone, the residuals for stars 2 and 3 would certainly suggest that those for the star n might be accidental ; but there is a striking accordance between the x residuals for the two plates which makes one hesitate to believe that the star n can be really the Nova, though this is far from impossible.

12. A word may be said as to the method of measurement. For the Max Wolf plate we simply bisected, as well as possible, the large and irregular images formed. The grain of the film is so large in proportion to them that it seems doubtful whether any systematic errors could be determined. But in the case of the Parkhurst plate, which was taken with a *reflector*, it becomes important to know how far the known systematic errors of reflector photographs could remove or diminish the residuals on a favourable supposition. Reflector images away from the plate centre are fan-shaped, and the apex of the fan corresponds to the ray reflected from the centre of the mirror. If we could measure the exact apex, we should get a true geometrical projection on the plate. Unfortunately the apex is in general cut off by the small mirror (or by the plate-holder itself), and cannot be measured. It is even difficult to estimate its position, owing to the photographic encroachment round the edges of the geometrical image. Mr. Plummer has suggested measuring the transverse axis of the fan, but the results of a trial of this method were not very satisfactory, and we seem almost driven to empirical rather than theoretical methods of measurement. But we may form a fair idea of the possible amount of error by measuring in different ways. The fan-shaped images on the Parkhurst plate were measured by each of two observers in two ways :

(*a*) Estimating the apex of the fan as well as possible.

(*b*) Estimating the centre of the transverse axis as well as possible.

The differences are as below. Of course, if they were constant throughout they would not affect the question at all.

TABLE III.

Star's No.	x Diff.		y Diff.	
	H.T.	B.G.	H.T.	B.G.
1	+012	+013	+008	+009
4	+009	+012	+008	+009
6	+015	+013	+006	+010
5	+012	+013	+004	+010
2	+006	+006	+004	+007
3	+008	+009	+010	+006
n	+010	+014	+008	+010

It will be clear that we cannot look to any great alteration of the residuals from methods of measurement.

13. On the whole, the evidence seems to be unfavourable to the view that the Nova is identical with the small star photographed before the outburst; but the question cannot be regarded as settled until the light of the Nova has faded sufficiently for search to be made for a small star some 5″ away. For the present it seems best to publish these figures without attempting to draw any final conclusion. But measures of these stars, especially of star 3, will be of great interest until the questions raised are settled.

University Observatory, Oxford:
1903 *August* 12.

P.S. September 14.—The printers' proof of the above was sent back to them yesterday. I have this morning received a letter from Professor Barnard which seems to show that the object photographed on February 16 and 19 is *not* identical with the Nova. He says, under date September 1, "This morning I got your Nova in *Gemini*. There is a small star 14^m preceding it which I measured, and which seems to be Mr. Parkhurst's star:

Position-angle 284°·3 Distance 7″·83.

I shall measure it again. The distances were measured under difficulties of approaching day, but I do not think the result can be more than $\frac{1}{2}$″ out. The Nova has got down to between the 11th and 12th magnitudes. It appeared hazy to me, like a hazy nebulous star. The seeing was good. It looks like Nova *Persei*, but I think is fainter."

A Derivation of Hill's Equation by a Direct Substitution.

By R. A. Herman, M.A.

(*Communicated by the Secretaries.*)

The method and most of the notation is that of Hill's paper on the "Motion of the Lunar Perigee," *Acta Mathematica*, vol. viii.

The equations satisfied by u and s are

$$\left.\begin{aligned} \mathrm{D}^2u + 2m\mathrm{D}u + 2\frac{\partial \Omega}{\partial s} &= 0 \\ \mathrm{D}^2s - 2m\mathrm{D}s + 2\frac{\partial \Omega}{\partial u} &= 0 \end{aligned}\right\} \quad \ldots \quad \ldots \quad (1)$$

which lead to Jacobi's Integral

$$\mathrm{D}u\mathrm{D}s + 2\Omega = 2C \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

We have if ψ be the angle made by the tangent with the axis of x

$$\mathrm{D}u = \zeta \frac{d}{d\zeta}(x+is) = e^{i\psi}\zeta\frac{d\sigma}{d\zeta}, \quad \mathrm{D}s = e^{-i\psi}\zeta\frac{d\sigma}{d\zeta}$$

where σ is the arc of the curve ; or if ϖ denote $\mathrm{D}u \,.\, \mathrm{D}s$,

$$\mathrm{D}u = e^{i\psi}\sqrt{\varpi}, \quad \mathrm{D}s = e^{-i\psi}\sqrt{\varpi}$$

Hence $2i\psi = \log(\mathrm{D}u/\mathrm{D}s)$; and

$$2i\mathrm{D}\psi = \frac{\mathrm{D}^2u}{\mathrm{D}u} - \frac{\mathrm{D}^2s}{\mathrm{D}s} \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

This gives $2i\varpi\mathrm{D}\psi = \mathrm{D}^2u\mathrm{D}s - \mathrm{D}^2s\mathrm{D}u$, and on substitution from (1)

$$\begin{aligned} 2i\varpi\mathrm{D}\psi &= -\mathrm{D}s\{2m\mathrm{D}u + 2\Omega_s\} - \mathrm{D}u\{2m\mathrm{D}s - 2\Omega_u\} \\ &= -4m\varpi - 2\Omega_s\mathrm{D}s + 2\Omega_u\mathrm{D}u \end{aligned}$$

Hence $$\Omega_u\mathrm{D}u - \Omega_s\mathrm{D}s = \varpi(2m + i\mathrm{D}\psi) \quad \ldots \quad \ldots \quad (4)$$

Differentiating (4)

$$\begin{aligned} \Omega_u\mathrm{D}^2u - \Omega_s\mathrm{D}^2s + (\Omega_{uu}\mathrm{D}u + \Omega_{us}\mathrm{D}s)\mathrm{D}u - (\Omega_{us}\mathrm{D}u + \Omega_{ss}\mathrm{D}s)\mathrm{D}s \\ = (2m + i\mathrm{D}\psi)\mathrm{D}\varpi + \varpi i\mathrm{D}^2\psi \end{aligned}$$

or substituting for Ω_u and Ω_s from (1)

$$\begin{aligned} m(\mathrm{D}u\mathrm{D}^2s + \mathrm{D}s\mathrm{D}^2u) + \Omega_{uu}\overline{\mathrm{D}u}^2 - \Omega_{ss}\overline{\mathrm{D}s}^2 = (2m + i\mathrm{D}\psi)\,\mathrm{D}\varpi \\ + \varpi i\mathrm{D}^2\psi \end{aligned}$$

giving the equation

$$(i\varpi\mathrm{D}^2\psi + \Omega_{ss}\overline{\mathrm{D}s}^2 - \Omega_{uu}\overline{\mathrm{D}u}^2) = -(m + i\mathrm{D}\psi)\mathrm{D}\varpi \quad \ldots \quad (5)$$

which will be useful later.

Let the point on the variational orbit receive an arbitrary tangential displacement δT and a normal displacement δN; then the corresponding values of δu, δs are respectively $(\delta T - i\delta N)e^{i\psi}$ and $(\delta T + i\delta N)e^{-i\psi}$.

Now subject the Jacobi Integral to an arbitrary variation,

$$Ds D\delta u + Du D\delta s + 2\Omega_u \delta u + 2\Omega_s \delta s = 0$$

or with the values for Du, Ds above

$$\begin{aligned} & e^{-i\psi}\sqrt{\varpi}e^{i\psi}\{D(\delta T - i\delta N) + (\delta T - i\delta N)iD\psi\} \\ & + \sqrt{\varpi}\ \{D(\delta T + i\delta N) - (\delta T + i\delta N)iD\psi\} \\ & + 2\Omega_u(\delta T - i\delta N)\frac{Du}{\sqrt{\varpi}} + 2\Omega_s(\delta T + i\delta N)\frac{Ds}{\sqrt{\varpi}} = 0 \end{aligned}$$

whence

$$\varpi D\delta T + \delta T . D\Omega + \varpi D\psi . \delta N + (\Omega_s Ds - \Omega_u Du) i\delta N = 0$$

On substitution from (2) and (4) this gives

$$[\varpi D - \tfrac{1}{2}D\varpi]\delta T = 2\varpi(m + iD\psi)i\delta N \quad \ldots \quad \ldots \quad (6)$$

We then vary the first equation of motion and obtain

$$D^2\delta u + 2mD\delta u + 2\Omega_{us}\delta u + 2\Omega_{ss}\delta s = 0$$

or on substitution

$$\begin{aligned} & e^{i\psi}[D^2(\delta T - i\delta N) + 2(m + iD\psi)D(\delta T - i\delta N) \\ & \quad + (iD^2\psi + 2miD\psi - D|\bar{\psi}|^2)(\delta T - i\delta N)] \\ & \quad + 2\Omega_{us}e^{i\psi}(\delta T - i\delta N) + 2\Omega_{ss}e^{-i\psi}(\delta T + i\delta N) = 0 \end{aligned}$$

and the equation obtained by varying the second equation of motion differs only in having the signs of i and m changed and Ω_{uu} in place of Ω_{ss}. Multiply these two equations by $e^{-i\psi}$, e^{i} and subtract; we obtain

$$\begin{aligned} & 2(m + iD\psi)D\delta T + (iD^2\psi + e^{-2i\psi}\Omega_{ss} - e^{2i\psi}\Omega_{uu})\delta T \\ & \quad = D^2 i\delta N + (2miD\psi - D|\bar{\psi}|^2)i\delta N \\ & \qquad + (2\Omega_{us} - e^{-2i\psi}\Omega_{ss} - e^{2i\psi}\Omega_{uu})i\delta N. \end{aligned}$$

Putting $(Ds)^2/\varpi$ for $e^{-2i\psi}$ and $(Du)^2/\varpi$ for $e^{2i\psi}$ the coefficient of δT on the left is $-\frac{1}{\varpi}(m + iD\psi)D\varpi$ by (5), and hence substituting from (6) the value of the left-hand side is $4(m + iD\psi)^2 i\delta N$.

The equation satisfied by δN is therefore $D^2\delta N = \Theta\delta N$, where

$$\Theta = m^2 + 3(m + iD\psi)^2 + e^{2i\psi}\Omega_{uu} - 2\Omega_{us} + e^{-2i\psi}\Omega_{ss}$$

It is easy to verify by change of variables that the terms involving Ω in this expression for Θ are $-\dfrac{\partial^2\Omega}{\partial N^2}$.

We have yet to express $-\frac{\partial^2 \Omega}{\partial N^2}$ in terms of the differentials of u and s.

Now $-\frac{1}{2}D\varpi = D\Omega = \Omega_u Du + \Omega_s Ds.$

Hence $-\frac{1}{2}D^2\varpi = \Omega_u D^2u + \Omega_s D^2s$

$$+ \Omega_{uu}(Du)^2 + 2\Omega_{us}DuDs + \Omega_{ss}(Ds)^2$$

$$= -\Omega_u(2mDu + 2\Omega_s) + \Omega_s(2mDs - 2\Omega_u)$$

$$+ \varpi\{e^{2i\psi}\Omega_{uu} + 2\Omega_{us} + e^{-2i\psi}\Omega_{ss}\}$$

$$= -2m\varpi(2m + iD\psi) - 4\Omega_u\Omega_s$$

$$+ \varpi\{e^{2i\psi}\Omega_{uu} + 2\Omega_{us} + e^{-2i\psi}\Omega_{ss}\}$$

Also $4\Omega_u\Omega_s = \{(\Omega_u Du + \Omega_s Ds)^2 - (\Omega_u Du - \Omega_s Ds)^2\}/\varpi$

$$= \frac{1}{\varpi}(D\Omega)^2 - \varpi(2m + iD\psi)^2$$

and this gives on substitution

$$e^{2i\psi}\Omega_{uu} - 2\Omega_{us} + e^{-2i\psi}\Omega_{ss}$$

$$= -\frac{1}{2\varpi}D^2\varpi + \frac{1}{4\varpi^2}(D\varpi)^2 + m^2 - (m + iD\psi)^2 - 4\Omega_{us}$$

$$= -D\left(\frac{D\varpi}{2\varpi}\right) - \left(\frac{D\varpi}{2\varpi}\right)^2 + m^2 - (m + iD\psi)^2 - 4\Omega_{us}$$

and since $$\Omega = \frac{K}{(us)^{\frac{1}{2}}} + \tfrac{3}{8}m^2(u+s)^2,$$

$$\Omega_{us} = \tfrac{3}{4}\frac{K}{r^3} + \tfrac{3}{4}m^2,$$

whence

$$\Theta = -\left(\frac{K}{r^3} + m^2\right) + 2(m + iD\psi)^2 - D\left(\frac{D\varpi}{2\varpi}\right) - \left(\frac{D\varpi}{2\varpi}\right)^2,$$

which is Hill's form.

On the Construction of Telescopes whose Relative or Absolute Focal Length shall be Invariable at all Temperatures. By F. L. O. Wadsworth.

(*Communicated by the Secretaries*)

In the case of all optical instruments which are designed for the accurate measurement of either relative or absolute positions it is extremely necessary to avoid the necessity for refocussing the instrument for changes of temperature. Such refocussing is likely to produce both errors of measurement and errors of adjustment. The first have already been dealt with in

a recent paper,* where the effect of refocussing is considered especially with reference to spectrometric, heliometric, and micrometric observations.† The second class of errors are more purely mechanical in their nature, and apply more particularly to measurements with the transit, meridian circle, zenith telescope, &c. Here the effect is to disturb the position of the axis of collimation, and may, of course, be eliminated by a redetermination of that constant. Such disturbances and readjustments are, however, to be avoided whenever possible. My attention was first called to this problem in working out the design of the proposed 6″ photographic transit and meridian circle for the new Allegheny Observatory,‡ and more recently by the experiences of Professor Updegraff with the new 6″ meridian circle of the U.S. Naval Observatory. Professor Updegraff found that the apparent focal length of this instrument was decidedly different at different seasons of the year. No such result had ever before been observed with any of the other similar instruments at the observatory, and Professor Updegraff stated to me that some of the observers there disputed and even ridiculed the idea of such a change taking place ; but, as a matter of fact, both the variability of the apparent focal length of the 6″ and the invariability of the focal length of the other instruments are fully explained and might have been predicted, by theory. There are a few points of interest in this connection which it has seemed desirable to develop.

The variability of the focal length of a refracting objective at different temperatures has been long known, but the cause of this variability does not seem to be well understood. The theory of the subject seems to have been first investigated by Krueger.§ Later, Sundell made an extended series of measurements of the focal length of the Helsingfors heliometer, and found‖ that the results obtained differed by more than 20 per cent. from those given by Krueger's formulæ. It was immediately pointed out by Professor Hastings¶ that this difference was probably due in large part to the error in Professor Krueger's assumption that the "refractive power" of a glass varies directly as the density. This assumption is now well known to be incorrect. The expression derived by Professor Hastings for the variation, ΔF, of the focal length of an objective for a difference in temperature, ΔT, is as follows :

$$\Delta F = -F^2\left[\frac{dn_1}{dt}A + (n_1 - 1)\frac{dA}{dt} + \frac{dn_2}{dt}B + (n_2 - 1)\frac{dB}{dt}\right]\Delta T \quad (1)$$

* "On the Optical Conditions required to secure Maximum Accuracy of Measurement in the Use of the Telescope and Spectroscope," *Astrophysical Journal*, vol. xvi. pp. 267–299 ; vol. xvii. pp. 1–19, 100–132.

† See particularly vol. xvii. pp. 7–19.

‡ See Report of the Director, 1900, pp. 8 and 29 ; *ibid.* 1901, p. 16.

§ *Astronomische Nachrichten*, Bd. 60, s. 65.

‖ *Ibid.* Bd. 103, s. 19–26 ; also Bd. 111, s. 257–262.

¶ *Ibid.* Bd. 105, s. 69–72.

where n_1 and n_2 are the indices of refraction of the crown and flint glasses for the wave-length corresponding to any given spectral focus of the objective, and A, B are the sums of the curvatures of the surfaces of the two lenses. All four differential coefficients, $\frac{dn}{dt}$ and $\frac{dA}{dt}$, must be determined by experiment.

The above expression (1) is derived directly from the differentiation of the usual expression for the focal length of a compound (achromatic) lens, and neglects the effect of thickness and separation of the two lenses. Ordinarily the effect of these quantities on the differential changes of focal length with temperature will be themselves differentials of a second order, and may be neglected. Within these limits therefore (1) is rigorously correct, provided the refraction coefficients $\frac{dn}{dt}$ are properly interpreted and measured. This last precaution, however, is an important one, and does not seem to have always been regarded. Thus Professor Hastings himself, in applying the formula to the calculation of the focal length of a given lens, seems to have used for $\frac{dn_1}{dt}$ and $\frac{dn_2}{dt}$ values derived from the measurements of variations in the *relative* indices of glass and air. This is correct only when the temperature of the lens is the *same* as that of the air and both change uniformly. Generally this last condition is not fulfilled, and we must then express $\frac{dn}{dt}$ with reference not to the *relative* index of refraction n, but with reference to the *absolute* indices, n_o and N_o, of glass and air respectively.

From the well-known relation

$$n = \frac{n_o}{N} \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

we have

$$\frac{dn}{dt} = \frac{1}{N}\frac{dn_o}{dt} - \frac{n_o}{N^2}\frac{dN}{dt} \simeq \frac{dn_o}{dt} - n\frac{dN}{dt} \quad \ldots \quad (3)$$

since N is itself very nearly equal to unity at all temperatures.

The value of the second term of (3) for any particular glass is nearly constant. According to the most recent determinations, the thermal refractive coefficient for air at ordinary pressure and temperature (760 mm. and 20° C.) is

$$\frac{dN}{dt} \simeq -0{\cdot}93 \times 10^{-6} \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

For the flint and crown glasses, Feil 1237 and Feil 1219,

investigated by Professor Hastings, the relative temperature coefficients for wave-lengths 5600 are*

$$\left.\begin{aligned} \text{Crown } 1219,\ \frac{dn_1}{dt} &= +0{\cdot}1\times10^{-6} \\ \text{Flint } \ 1237,\ \frac{dn_2}{dt} &= +5{\cdot}4\times10^{-6} \end{aligned}\right\} \quad \ldots \quad \ldots \quad (5)$$

The relative indices, n, for these two glasses for the same wave-lengths are

$$n_1 = n_{1219} = 1{\cdot}519+$$
$$n_2 = n_{1237} = 1{\cdot}628$$

Hence the absolute temperature coefficients $\frac{dn_0}{dt}$ are found to be

$$\text{For crown } 1219,\ \frac{dn_0}{dt} \simeq -1{\cdot}31\times10^{-6}$$

$$\text{For flint } 1237,\ \frac{dn_0}{dt} \simeq +3{\cdot}9\times10^{-6}$$

The effect on the focal length of a given change in the temperature of the air in the telescope tube is therefore very nearly equal to the effect of the same change in the temperature of the crown glass, and is not quite one-third as great as that produced by an equal temperature variation in the flint. In the first case the effects are nearly compensatory ; in the second case they are additive. Hence any difference in the temperature variation, Δt, of the air and the objective will produce a decided difference in the quantity $\frac{dn}{dt}$ which appears in (1) and (3), and will lead to a corresponding difference in ΔF. In general the temperature change in the glass will lag behind that in the surrounding air ; hence, if the temperature is rising the quantity $\frac{dn}{dt}$ will be smaller than would be indicated by measurement, and the observed focal length will be shorter than that calculated for the given air temperature ; if the temperature is falling, the reverse will be the case, and the measured focal length will be longer than the calculated. This fact may explain the discrepancies that have been sometimes observed in measuring the variations of focal length with temperature.

The magnitude of the differential change in the focal length of a given telescope is dependent upon the nature of the glass employed in its construction. For the purpose of comparison I have collected the results of measurements on a number of different object-glasses of different sizes and types of construction, which are presented in the following table :—

* *American Journal of Science*, vol. xv. p. 269.

TABLE I.

Instrument.			Change in F.				Conditions of Observation.		
Objective.	A	F.	ΔT(C).	ΔF (apparent).	ΔZ (tube).	Total $\frac{\Delta F}{F\Delta T}=\alpha''$.	Observer.	Reference.	Remarks.
	cm.	cm.		cm.	cm.				
Helsingfors	...	...	28°·1	0·177		2·19 × 10−5	Sundell	Ast. Nach. Vol. ciii. p. 24	Winter of 1879 16°·2 C. to −11°·9 C.
Heliometer	...	298·3	31·9	0·211		2·29 × 10−5	Sundell	Vol. cxi. p. 261	Winter of 1881 17°·3 C. to −14°·6 C.
Strassburg Heliometer	...	691·6	27·8	1·08		5·1 × 10−5	Schur	Ast. Nach. Vol. cxix. p. 249	+24°·6 C. to −3°·2 C.
Göttingen Heliometer	...	...	About 40	...		2·06 × 10−5	Schur	Ambronn. Handbuch	—
Emerson McMillen	30·5	457·2	27·5	0·18	0·13*	2·46 × 10−5	Lord	Astrophysical Journal, Vol. v. p. 305	Change measured for H_β
Halstead	58·4	917·7	30·0	Very small	0·22†	1·17 × 10−5	Young	From unpublished observations	Never very carefully observed
Washington	66·0	990·0	About 24·4	0·24	0·27†	2·11 × 10−5	See and Dinwiddie	Report U.S. Naval Obs. 1902	Visual change
Lick	91·4	1763· +	30	1·7	0·6*	4·3 × 10−5	Campbell	Astrophysical Journal, Vol. viii. p. 138	Change measured for H_γ
Yerkes	102·0	1936· +	50	0·72	0·97*	1·64 × 10−5	Hale and Ellermann	Astrophysical Journal, Vol. x. p. 93.	Not stated, probably visual

* Computed for steel tube.

† Computed for combination tube (steel and brass).

The wide variations in the absolute values of the temperature co-efficients α'' is remarkable, and seems to indicate that little attention has been paid to the question of controlling or eliminating changes in focal length. But as already stated, this question is an important one in the case of instruments designed for accurate measurements, and should in such cases be quite as carefully considered as any of the other optical problems connected with the design of objectives.

In general, the condition which we desire to fulfil is that the apparent focal length of the instrument shall remain unaltered. This means that the coefficient of change in focal length α'' shall be equal to the coefficient of linear expansion α_t of the metal of which the tube of the telescope is constructed, *i.e.*

$$\alpha'' = \frac{\Delta F}{F} = \alpha_t = \frac{\Delta Z}{Z} \quad \ldots \quad \ldots \quad \ldots \quad (6)$$

Equation (1) may be put in the form

$$\frac{\Delta F}{F} = -F\left\{\frac{dn_1}{dt}A + \frac{dn_2}{dt}B - \alpha_g\left[(n_1 - 1)A + (n_2 - 1)B\right]\right\}\Delta t$$

or for one degree change in temperature, ($\Delta t = 1$)

$$\frac{\Delta F}{F} = \alpha'' = \alpha_g - F\left(\frac{dn_1}{dt}A + \frac{dn_2}{dt}B\right) \quad \ldots \quad (7)$$

where α_g is the coefficient of linear expansion of the glass, which is assumed to be the same for both flint and crown.

In order to satisfy the conditions of achromatism, we must also have for A and B—

$$\left.\begin{aligned} A &= \frac{1}{F\Delta n_1\left[\dfrac{n_1 - 1}{\Delta n_1} - \dfrac{n_2 - 1}{\Delta n_2}\right]} \\ B &= \frac{1}{F\Delta n_2\left[\dfrac{n_2 - 1}{\Delta n_2} - \dfrac{n_1 - 1}{\Delta n_1}\right]} \end{aligned}\right\} \quad \ldots \quad \ldots \quad (8)$$

Substituting these values of A and B in (7) we obtain

$$\left.\begin{aligned} \alpha'' &= \alpha_g - \frac{\dfrac{dn_1}{dt}}{\Delta n_1\left[\dfrac{n_1 - 1}{\Delta n_1} - \dfrac{n_2 - 1}{\Delta n_2}\right]} - \frac{\dfrac{dn_2}{dt}}{\Delta n_2\left[\dfrac{n_2 - 1}{\Delta n_2} - \dfrac{n_1 - 1}{\Delta n_1}\right]} \\ &= \alpha_g + \frac{1}{\dfrac{n_1 - 1}{\Delta n_1} - \dfrac{n_2 - 1}{\Delta n_2}}\left[\frac{1}{\Delta n_2}\frac{dn_2}{dt} - \frac{1}{\Delta n_1}\frac{dn_1}{dt}\right] \end{aligned}\right\} \quad (9)$$

and the problem is to choose two glasses (crown and flint) whose

optical properties are such as to make the numerical value of a'' from (9) satisfy the condition expressed in (6)

Through the researches of Fizeau,* Hastings,† Müller,‡ Vogel,§ Pulfrich,‖ Reed,¶ and Winkelmann** we now have available the constants a_g, n, Δn, and $\frac{dn}{dt}$ for a considerable number of flint and crown glasses. These values are collected together in the following table :—

* *Annales de Chimie et de Physique* (3), vol. lxvi. p. 429.
† *American Journal of Science* (3), vol. xv. p. 269.
‡ *Publicationen des Astrophysicalischen Observatoriums zu Potsdam*, vol. iv. p. 151.
§ Wiedmann, *Annalen*, vol. xxv. p. 87.
‖ *Ibid.* vol. xlv. p. 609.
¶ *Inaugural-Dissertation*, Jena, 1897.
** Wiedmann, *Annalen*, 1892 to 1897.

TABLE

Glass.	Maker's Number.	Sp. gr.	α_t 1×10^{-6}	n_D for D.	$\frac{1}{\Delta n}(n_D-1)$ C–F.
Flint	Feil 1237	3·554	8·5	1·62542	36·1
Flint	„ 1241	3·151		1·58091	41·0
Crown	„ 1219	2·482		1·51796	58·5
Crown (Zinc)	Maes	2·626	8·5	1·5204	...
Flint (ordinary)	...	3·584	8·1	1·6112	...
Dense Flint	...	4·14	6·6	1·682	...
Flint	Schröder	3·855	...	1·65129	33·8
Flint	„	3·642	...	1·62461	36·5
Flint	„	3·218	...	1·57991	41·4
Crown	„ 1308	2·519	...	1·51767	59·3
Crown	„ 1313	2·522	...	1·51614	58·6
White Glass	...	...	...	1·61399	36·5
Heavy Flint	...	...	...	1·75968	26·8
Super Dense Silicate Flint	S 57	6·33	9·3	1·9625	19·7
Extra Dense „ „	O 165	...	8·0	1·7545	27·6
Ordinary „ „	O 544	...	...	1·6130	37·1
Light „ „	O 154	...	7·9	1·5710	43·1
Light Barium Flint	O 527	3·19	9·0	1·5718	50·6
Light Borosilicate Flint ...	O 658	...	5·2	1·5452	50·3
Heavy Barium Silicate Crown	O 211	3·21	...	1·5727	58·0
Phosphate Crown ...	S 40	3·07	...	1 5619	66·5
Ordinary Silicate Crown	O 1022	...	9·6	1 5173	60·2
Light Phosphate „	O 225	2·58	...	1·5160	70·3
Borosilicate „	O 627	...	8·0	1·5128	63·7
Light Borate „	S 205	...	6·7	1·5075	60·6
Super Dense Silicate Flint	S 163	...	...	1·8904	22·3
Flint	O 1299	...	...	1·6099	57·7

The desired equality between α_t and α'' required to fulfil the condition of apparent invariable focal length may be obtained by varying either α_t or α'', *i.e.* by a suitable choice either of the material of which the telescope tube is made, or of the glasses which are used in the construction of the objective.

The materials at our practical disposal for the telescope tube, and their thermal co-efficients of expansion, α_t, are as follows :

Zinc $\alpha_t = \alpha_2 \mathrel{\tilde{=}} +29$ to 30×10^{-5}

Aluminium $= \alpha_a \mathrel{\tilde{=}} +23 \times 10^{-5}$

II.

$\frac{dn_o}{dt}$ for D. $\times 10^{-6}$	$\frac{dn}{dt}$ for D $\times 10^{-6}$	n for G.	$\frac{1}{\Delta n}(n_{G-1})$ F−H	$\frac{dn_o}{dt}$ for G $\times 10^{-6}$	$\frac{dn}{dt}$ for G $\times 10^{-6}$	Observer.
+ 3·9	+ 5·07	1·64909	29·5	...	+ 7·85	Hastings.
...	+ 2·61	1·60013	34·0	...	+ 4·51	
− 1·31	− 0·08	1·52960	51·5	...	+ 1·44	
...	0·0	...	...	...	...	Fizeau.
...	+ 2·6	...	...	...	...	
...	+ 6·87	...	...	...	...	
...	+ 5·3	1·67688	...	...	+ 7·8	Müller.
...	+ 6·2	1·64725	30·5	...	+ 8·7	
...	+ 3·6	1·59831	35·1	...	+ 5·6	
..	− 0·09	1·52880	53·5	...	+ 1·1	
...	− 0·01	1·52737	52·6	...	+ 1·1	
...	+ 2·4	1·636033	...	...	+ 4·3	Vogel.
...	+ 3·2	1·78915	...	...	+ 8·0	
+14·5	+15·9	2·0303	...	+28·1	+29·5	Pulfrich.
+ 7·7	+ 9·1	1·7914	...	+13·1	+14·4	
+ 2·8	+ 4·0	1·6348	31·1*	+ 5·0	+ 6·2	
+ 2·6	+ 3·7	1·5883	36·8*	+ 4·1	+ 5·2	
+ 0·14	+ 1·25	1·5864	41·9*	+ 1·37	+ 2·5	
+ 3·0	+ 4·1	1·5591	...	+ 4·1	+ 5·2	
+ 0·4	+ 1·5	1·5852	...	+ 1·4	+ 2·55	
− 3·05	− 1·94	1·5725	...	− 2·37	− 1·24	
− 1·05	+ 0·04	1·5281	54·0*	− 0·10	+ 1·0	
− 1·90	− 0·80	1·5252	...	− 1·42	− 0·31	
+ 1·37	+ 2·51	1·5229	57·5*	+ 2·13	+ 3·29	
− ·74	+ ·33	1·5179	54·5*	− 0·0	+ 1·06	
+12·8	+14·10	1·9441	...	+21·6	+23·0	Reed.
+ 4·1	+ 5·25	1·6231	...	+ 5·3	+ 6·4	

Brass and Bronze $= a_b \simeq +18$ to 19×10^{-6}

Copper $= a_c \simeq +16$ to 17×10^{-6}

Steel and Iron $= a_s \simeq +10$ to 13×10^{-6}

Glass $= a_g \simeq +6$ to 9×10^{-6}

Wood $= a_w \simeq +0{\cdot}3$ to $0{\cdot}8 \times 10^{-6}$

Nickel Steel $= a_n \simeq +0{\cdot}1$ to $0{\cdot}5 \times 10^{-6}$

Of these only aluminium, brass, copper, steel, and nickel steel are suitable for large telescopes. These metals offer a range of values for a from 0 to 23×10^{-6}. In order to fulfil the general condition in (6) the thermal coefficient of focal change a'' must therefore not exceed the first figure, *i.e.* 23×10^{-6}. If the absolute focal length is to remain invariable, both a_t and a'' must be zero.

Since a_t, a_μ, n, dn and $\frac{dn}{dt}$ are all themselves functions of t, it is necessary to choose some common standard temperature, t_0, which will be a mean of the extremes within which we desire to secure compensation. For laboratory work the value of t_0 will be about 20° C., and the maximum range of temperatures will probably not exceed $\pm 10°$ C. For astronomical work the mean temperature t_0 will be about 10° lower, *i.e.* $t_0 = 10°$ C., and the maximum range may be as large as $\pm 20°$, *i.e.* from $-10°$ C. to $+30°$ C. Since the variability of the various optical constants which appear in (9) with temperature will prevent *exact* compensation for all values of t, it is important to fix the limits within which variations of focus may be permitted without detriment to the optical performance of the instrument. If the instrument is used simply for visual work, and no requirement more severe than that of "good definition" is imposed, the permissible variation in focus will be *

$$\delta F = \frac{\lambda}{\beta^2} \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

where β is the semi-angular aperture of the lens. For purpose of comparison with (6) and (9) we may put this in the form

$$\frac{\delta F}{F} = \frac{2\lambda}{a} \cdot \frac{1}{\beta} \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

The absolute value of the permissible variation in focus δF is the same, (10), for all instruments having the same form (*i.e.* same angular aperture). The percentage change $\frac{\delta F}{F}$ is inversely proportional to the linear aperture, a, as well as to the semi-angular aperture, β. In the case of an ordinary meridian circle, β is not far from 0·04 and a is about 15 cm. Hence for minimum focus, for which λ is about 0·000056 cm., we have

$$\frac{\Delta F}{F} \sim = 185 \times 10^{-6}$$

as the extreme permissible variation of focus with temperature. If the range of t is 40°, as assumed above, this gives as the permissible range for 1°

$$\frac{\delta F}{F} = a'' - a \sim = 4{\cdot}6 \times 10^{-6} \quad \ldots \quad \ldots \quad (12)$$

* Lord Rayleigh "On the Accuracy of Focus required for Sensibly Perfect Definition," *Phil. Mag.*, vol. xx, p. 354.

Hence in this case, if the values of α'' and α_t agree within four units in the sixth decimal place, there will be no *apparent* change in focus over a range of 40° C.

With the ordinary flint and crown glasses, Feil 1237 and 1219, used by Hastings, the value of α'' is found to be *

$$\alpha'' = 22+ \times 10^{-6} \quad \ldots \quad \ldots \quad (13)$$

The values of α for brass, the material of which the tubes of nearly all our transits and meridian circles are composed, is about 18×10^{-6}. The apparent change in focus for 1° C. of an instrument so constructed is

$$\frac{\delta F}{F} = \delta_F = \alpha'' - \alpha_b = 4 \times 10^{-6} \quad \ldots \quad \ldots \quad (14)$$

which is well within the limit imposed by (12). Such an instrument will, as a matter of fact, maintain an apparently invariable focus over a range of temperature of nearly 50° C. ; a considerably greater range than is ever met with in astronomical work of precision. Observers with meridian circles of the usual construction may thus be readily led to doubt the existence of any relative change in focus in such instruments.

If, however, we construct the telescope tube of steel, as in the case of the new Washington 6″ meridian circle and 5″ alt-azimuth, we have for the same objective above considered

$$\delta_F = \alpha'' - \alpha_s \simeq \times 10^{-6}$$

and in this case the apparent focus would change for any temperature variation exceeding 15°. For a difference of temperature of 25° C., which is about the range of temperature at Washington, the total apparent variation in focus of the 6″ (focal length 182·9 cm.) will be

$$\delta F = 3 \times 10^{-4} F$$
$$= \cdot 055 \text{ cm.}$$

or a little over two one-hundredths of an inch. This is almost exactly the amount of variation found by Prof Updegraff.†

An examination of Table I. shows that in the case of visual refractors the value of α'' ranges from about that computed in (13) to one about 50 per cent. larger. The results of the preceding comparison show that in order to obtain compensation with a steel tube, the values of α'' must be reduced about one-half. Since the value of α_1 for most glass is not far from 8×10^{-6}, it follows that the term involving the relations between n, Δn, and $\frac{dn}{dt}$ must be nearly zero to secure the desired equality between the values of α'' and α_s (steel tube). The dispersion

* *Astronomische Nachrichten*, Bd. 105, s. 62.

† From data communicated in advance by Prof. Updegraff. See also Vol. III. *Publications of the United States Naval Observatory*, Part iv., p. D. vi.

coefficients $\frac{n-1}{\Delta n}$ are always considerably larger for crown glass (n_1) than for flint glass (n_2), and the coefficient of the quantity within the brackets is therefore always positive and greater than zero. The mean dispersion Δn_2 of flint glass is, on the contrary, always larger than the corresponding quantity Δn_1 for crown, and by an examination of the values of $\frac{dn}{dt}$ in Table II. we find that in general this refraction coefficient is likewise much larger for flint than for crown. To reduce the value of a'' it is therefore necessary to choose a flint and crown in which the ratios $\frac{dn}{dt} : \Delta n$ are nearly equal. For convenience of comparison I have computed this ratio, which we will designate by R, for each of the glasses of Table II. for the region near D (for which visual objectives are corrected) and also for the region near G (for photographic objectives) whenever the data available were sufficient for the latter determination. The results, together with the values of a_1, and of the dispersion coefficients $\frac{n-1}{\Delta n}$, taken from Table II., are arranged systematically for the flints and crowns separately in Table III. and Table IV.

TABLE III.

Flints.

GLASS	a'	D Region (Visual Objectives)		G Region (Photographic Objectives)		Remarks with Reference to Physical Properties.
	1×10^{-6}	$\frac{n_2-1}{\Delta n_2}=D_2$	R_2 1×10^{-6}	$\frac{n_2-1}{\Delta n_2}=D'_2$	R'_2 1×10^{-6}	
Densest Silicate S 57	9·3	19·7	326	...	...	Very yellow.
Silicate S 163	...	22·3	353	...	...	„
Dense Vogel (V) ...	...	26·8	113	...	...	„
Silicate O 165 ...	8·0	27·6	332	...	...	
Schroeder (S_1) ...	...	33·8	276	...	...	
Feil 1237	8·5	36·1	293	29·5	357	
Schroeder (S_2) ...	...	36·5	362	30·5	410	
White Flint (V_2) ...	...	36·5	143	...	...	
Ordinary Flint O 544... ...	...	37·1	244	31·1	304	Good.
Feil 1241	8·5	41·0	185	34·0	255	
Schroeder (S_3) ...	...	41·4	257	35·1	321	
Light Silicate O 154	7·9	43·1	280	36·8	325	
Borosilicate O 658	5·2	50·3	379	...	...	Very permanent.
Barium O 527 ...	9·0	50·6	111	41·9	179	Not good.
„ O 1299		57·7	387	...	...	

TABLE IV.

Crowns.

GLASS.	α_1	D Region (Visual Objectives) D_1	R_1	D Region (Photographic Objectives) D'_1	R'_1	Remarks on Physical Properties.
	1×10^{-6}		1×10^{-6}		1×10^{-6}	
Heavy Barium Silicate O 211	...	58·0	+152·0	...	...	Liable to tarnish.
Feil 1219 ...	8·5	58·5	− 9·0	51·5	140	
Schroeder 1313 ...	...	58·6	− 1·14	52·6	110	
„ 1308 ...	...	59·3	− 10·4	53·5	111	
Ordinary Silicate O 1022 ...	9·6	60·2	+ 4·65	54·0	102	
Light Borate S 205	6·7	60·6	+ 39·3	54·5	112	Must be protected in use.
Borosilicate O 627	8·0	63·7	+310·0	57·5	362	Very permanent.
Phosphate S 40	...	66·5	−229·0	...	...	Not desirable.
Light Phosphate O 225 ...	...	70·3	−110·0	...	...	

By proper selection of the flint and crown from these two tables we can obtain objectives having almost any desired value of α''. A few examples may be of interest.

(A)$_v$ For $\alpha'' = \alpha_b$ (brass tube mounting)

(1) The combination of Feil 1237 (flint) with Feil 1219 (crown) gives, as already stated, an objective whose coefficient α'' of focal length variation is so close to that of brass that the apparent focal length of such an objective in a brass tube will remain apparently invariable over a range of 50° C.

A still more accurate compensation may be obtained by (2) the combination of ordinary silicate flint, O 544, with ordinary silicate crown, O 1022. The mean thermal coefficient of expansion α_g of these glasses is about $9{\cdot}5\times10^{-6}$. We obtain for α''

$$\alpha'' = \left[9{\cdot}5 + \frac{1}{60{\cdot}2-37{\cdot}1}(\cdot244-4{\cdot}7)\right]\times10^{-6}$$
$$= 19{\cdot}5\times10^{-6}$$

The coefficient of apparent change in focus for such an objective in a brass mounting for 1° C. is therefore

$$\delta_F = (19{\cdot}5-18 = 1{\cdot}5)\times10^{-6}$$

and by comparison with (11) and (12) we see that for instruments of less than 6″ aperture the compensation is apparently perfect over a range of more than 100° C. For instruments up

to 12″ aperture the compensation is effective over a range of 50° C.

(B)$_v$ For $a'' = a_s$ (steel tube compensation).

To secure this result it is necessary, as already stated, to use glasses for which R_1 and R_2 are nearly equal. Two combinations which satisfy this condition are as follows :—

(1) Combine Feil 1241 (flint) with a heavy barium silicate crown, O 211. The mean value for the coefficient a_g for these glasses is about $8{\cdot}5 \times 10^{-6}$. For a'' we have

$$a'' = \left[8{\cdot}5 + \frac{1}{58-41}(185-152)\right] \times 10^{-6}$$
$$= 10{\cdot}5 \times 10^{-6}$$

and $$\delta_F \simeq 0{\cdot}5 \times 10^{-6}$$

which would ensure compensation (for a 6″ objective) over a range of nearly 300° C. The combination, however, will require quite thick lenses and relatively deep curves to secure the necessary corrections for spherical and chromatic aberration. The barium silicate crowns are also less permanent than some of the others. A better combination is as follows :

(2) Combine Feil 1237 (flint) with a borosilicate crown O 627. This gives for a''

$$a'' = (8{\cdot}5 - 6 = 7{\cdot}9) \times 10^{-6}$$

and $$\delta_F = 2{\cdot}1 \times 10^{-6}$$

which ensures compensation (for 6″ objective) over a range of more than 80° C.

(C)$_v$ For $a'' = 0$ (focal length invariable).

To secure this condition we must necessarily use a crown having a large positive value of R. The only crowns in the above list which satisfy this condition are the two used in the combinations ($a'' = a_s$) just considered. With these we must use flints whose thermal variations are small—*i.e.* dense flint, V_1 ; white flint, V_2 Feil 1241, or light barium flint, O 527. The commercial source of the first two is uncertain, and the last is unsatisfactory—in fact, inadmissible, in combination with the first crown mentioned (O 211). The best combination therefore appears to be :

(1) Flint, Feil 1241, with crown O 627. This gives

$$a'' = [8{\cdot}5 - 5{\cdot}5 = 3] \times 10^{-6}$$

which is invariable within limits of possible accuracy of focussing over a range of about 60° C. for a 6″ objective.

In the case of photographic objectives the conditions of com-

pensation and absolute invariability of focus are met by the combinations :

$(A)_p$ Compensation in brass-tube mounting.

Flint O 344 (ordinary) and crown O 1022 (ordinary).

$$a'' \cong 18 \times 10^{-6} \text{ and } \delta_F \cong 0{\cdot}0$$

$(B)_p$ Compensation in steel-tube mounting.

Flint, Feil 1237, and crown O 627.

$$a'' = a_1 = 8{\cdot}5 \times 10^{-6} \text{ and } \delta_F = 1{\cdot}5 \times 10^{-6}$$

$(C)_p$ Constant focal length.

Flint, Feil 1241, and crown O 627.

$$a'' \cong 3{\cdot}6 \times 10^{-6},$$

Or flint O 527, and crown O 627.

$$a'' \cong -2{\cdot}5 \times 10^{-6}.$$

It is to be noted that all the above results are obtained without imposing any conditions as to radii of curvature of either of the lenses, and therefore without sacrifice of any of the usual optical requirements in respect to chromatic and spherical aberration, flatness of field, &c. The numerous advantages resulting from relative and absolute invariability of focus in photographic charting, in transit and meridian-circle observations, in heliometric and micrometric observations, in spectroscopic determinations of absolute wave-length and motion in the line of sight, and in fact in all work in which accuracy is of the first importance, are so readily perceived that no argument is necessary to make apparent the great desirability of so constructing our objectives as to fulfil the above conditions. The preceding examples show this to be possible within extended temperature ranges by using glasses which are easily obtainable, and which, with perhaps one possible exception, have no objectionable physical characteristics. At the same time it may be remarked that our knowledge of the thermal coefficients of expansion α_g and of refraction are less complete than they should be to secure the best results, particularly in the construction of photographic objectives. These quantities should be obtained for a larger number of the Jena glasses, and particularly for the more important varieties of Mantois glasses, concerning which we have at present no information whatever.

In work demanding the very highest degree of accuracy, the requirements in reference to knowledge of the exact focal length of the instrument at any given temperature are sometimes more severe than those imposed by the conditions in (10) and (11), which are based on considerations of visual definition only. The conditions of maximum accuracy, which have been examined

in the paper to which reference has already been made,* demand that the focal lengths be known or maintained constant to the degree of accuracy determined by the relation †

$$\delta_F = \frac{2\lambda}{a} \cdot \frac{1}{30\kappa} \quad \ldots \quad \ldots \quad \ldots \quad (15)$$

where κ is the angular field of measurement. For points very near the centre of the field, the accuracy of focus demanded by (15) is no greater than that demanded by (11), but for points at any distance from that axis the necessary accuracy is increased in the ratio

$$q = \frac{30\kappa}{\beta} \quad \ldots \quad \ldots \quad \ldots \quad (16)$$

In a 6″ meridian circle the maximum field of measurement is only about 1′·2. Hence $30\,\kappa \cong \cdot 01$ and

$$q = \tfrac{1}{4}$$

i.e. the accuracy of focus necessary for good definition is more than sufficient to eliminate sensible errors of measurement due to field.

In the case of the heliometer and filar micrometer the conditions are different. Here the field measured is frequently as large as 30′. For such a case $30\,\kappa \cong 0{\cdot}26$ and $q \cong 6{\cdot}5$; *i.e.* the permissible change in focus is only about one-seventh as great as is allowed by considerations of visual definition alone. On this basis the total variation of focal length with temperature for a 6″ objective must not exceed

$$\frac{\Delta F}{F} = \frac{185}{6{\cdot}5} \times 10^{-6} \cong 30 \times 10^{-6},$$

or for 1° C. as before

$$\delta'_F(\text{max.}) = \frac{30 \times 10^{-6}}{\Delta T} \quad \ldots \quad \ldots \quad (17)$$

ΔT being the total range in temperature.

In spectrographic work the requirements are still more severe on account of the larger field used. For large modern spectrographs, κ may be as large as 1°·5.‡ The maximum values of a, however, do not exceed 5 cm. For these values of κ and a, δ_F becomes as before,

$$\delta_F(\text{max.}) = \frac{30 \times 10^{-6}}{\Delta T} \quad \ldots \quad \ldots \quad (18)$$

* *Astrophysical Journal*, vol. xvi. pp. 267–299; vol. xvii. pp. 1–19, 100–132.

† *Loc cit.* See equation (66).

‡ Larger fields than this are sometimes used, but, as the writer has shown, at a very probable sacrifice of accuracy. *Loc. cit.* vol. xvi. pp. 281–282; vol. i. pp. 33, 110–111.

To obtain the best results in heliometric, micrometric, and spectroscopic measurements, the work must be conducted under less extreme temperature variations than have been assumed in meridian circle work. If for these observations we assume the maximum value of ΔT to be 20°, we have for δ_F(max.) for 6″ and 2″ telescopes, respectively

$$\delta'_F(\text{max.}) = 1{\cdot}5 \times 10^{-6} \quad \ldots \quad \ldots \quad (19)$$

Comparing this value of δ'_F with those obtained by combinations $(A)_v$, $(B)_v$, $(C)_v$, $(A)_p$, $(B)_p$, and $(C)_p$, we see that the conditions for heliometric and micrometric work are fully satisfied for apertures not exceeding 6″ by the visual objectives $(A)_v$ (2) in a brass tube mounting ; and $(B)_v$ (1) in a steel tube mounting. The conditions for spectrographic work are similarly satisfied for linear apertures not exceeding 2″ by the photographic objectives $(A)_p$ and $(B)_p$.

Very large objectives like the 36″ Lick and the 40″ Yerkes have angular apertures considerably smaller than that assumed in computing (12) and (19). For the Yerkes 40″ $a \cong 102$ cm. and $\beta \cong {\cdot}026$. Hence, for a maximum temperature range of 40°, the requirements of visual definition demand a maximum apparent change in focus not exceeding

$$\delta_F = 1 \times 10^{-6} \quad \ldots \quad \ldots \quad \ldots \quad (20)$$

For such large instruments the only possible mounting is (B), (steel tube). The condition expressed in (20) is fulfilled for only one combination, *i.e.* B_v (1). This, as already stated, is not altogether satisfactory on account of the character of the crown used. The second combination, $(B)_v$ (2), is satisfactory on this score, but has a somewhat too small coefficient of variation, δ_F.

In such cases as this we may secure *exact* compensation by constructing the tube of the telescope in two sections which are of different materials. We shall then have for each degree change in temperature

$$\frac{\delta Z}{dt} = S_1 a_1 + S_2 a_2$$

and

$$S_1 + S_2 = F.$$

For exact compensations

$$\frac{\delta F}{dt} = a'' F = S_1 a_1 + S_2 a_2$$

or

$$\frac{S_1}{F} = \frac{a'' - a_2}{a_1 - a_2} \text{ and } \frac{S_2}{F} = \frac{a'' - a_1}{a_2 - a_1} \quad \ldots \quad \ldots \quad (21)$$

For the case above considered, $a'' = 7{\cdot}9$, $a_1 = 10$, and a_2 must

therefore be smaller than a_1. If we make the section S_2 of nickel steel, $a_2 = a_n \cong 0{\cdot}2$, and we get for S_1 and S_2

$$S_1 \cong 0{\cdot}79\ F$$
$$S_2 \cong 0{\cdot}21\ F$$

i.e. about four-fifths of the tube should be of ordinary steel sheet and the remaining one-fifth of nickel steel sheet. When a'' is larger than a_1, the section S_2 must of course be made of brass, copper, or aluminium.

In the preceding examples we have endeavoured to meet the conditions of apparent invariability of focus from the standpoint, first, of visual definition, and, secondly, from that of accuracy. In the latter case there is still one further consideration which it is of importance to consider, *i.e.* the constancy of the value of one scale or screw division of the measuring or recording device. In the case of direct micrometric or heliometric measurements at the focal plane, this constancy can be secured, as we have previously shown,* by satisfying the relation

$$a' = a_t = a'' \quad \ldots \quad \ldots \quad \ldots \quad (22)$$

i.e. by making the screw or scale of material having a mean coefficient of expansion a' equal to that of the telescope tube itself. That is, we may in such cases eliminate all sensible changes in the micrometer or heliometer constants in any one of the objectives, $(A)_v$, $(B)_v$, or $(C)_v$, by making the screws or scales of these instruments of brass, steel, and nickel steel respectively.

In the case of photographic instruments we must, in order to always obtain a constant scale of record, satisfy the condition

$$a' = a_g = a'' \quad \ldots \quad \ldots \quad \ldots \quad (23)$$

and to meet this requirement, together with that of (11) or (15), we can only use one of two materials for the telescope tube, *i.e.* either steel or glass. Of these, steel is of course structurally preferable, and its coefficient, a_s, is fortunately so near the coefficient a_g that the objective $(B)_p$, whose coefficient a'' is between a_s and a_g, will, if mounted in a steel tube, have the two very desirable properties of requiring no focussing (over ranges of temperature less than 20° C),† and of yielding photographic records whose scale at any standard temperature t_0 will always be the same. Such a construction is of course of the greatest value for spectrographic determinations of absolute wave length and motion in the line of sight, photographic observations for stellar

* *Loc. cit.* vol. xvii. p.

† If constancy of focus over a large range is required, it can be obtained by use of a composite tube of ordinary steel and nickel steel as already described.

parallax, and similar work in which the elimination of all small errors due to temperature variations in the apparatus itself is of fundamental importance.*

* In the case of prism spectrographs, another serious source of error is found in the temperature variations in the dispersing train. These may also be largely eliminated by proper construction of the prisms. This subject has been taken up in another paper: "Effect of Temperature Variations on the Deviation of Prism Trains and on Methods of Eliminating such Effects," now in preparation for the *Astrophysical Journal.*

Allegheny Observatory:
1902 *December.*

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"Preliminary Note on the Relationships between Sun-spots and Terrestrial Magnetism." By C. CHREE, Sc.D., LL.D., F.R.S. Received December 18, 1902,—Read January 22, 1903.

(From the National Physical Laboratory.)

I have been engaged during the last two years on an analysis of the magnetic results obtained at Kew Observatory (now the National Physical Laboratory), during an 11-year period, 1890 to 1900. The work has been much interrupted, and is still incomplete. Amongst the points dealt with is the inter-relationship between sun-spot frequency and magnetic phenomena, and, as this has recently been engaging attention elsewhere, I have decided to put certain of my results on record at once. It has long been known from the researches of Balfour Stewart, Ellis, and others, that there is a close connection between the times of occurrence of greatest sun-spot frequency and largest amplitude of the diurnal inequality of magnetic declination and horizontal force. I have investigated whether the numerical relationship between the phenomena can be adequately represented mathematically in a simple way.

A convenient basis for the investigation was presented by the publication by Professor Cleveland Abbe in the 'U.S. Monthly Weather Review,' for November, 1901, of a table of sun-spot frequencies as calculated by Wolf and Wolfer for a very long series of years. After I had carried out all the calculations, Wolfer himself published a similar table* embodying his latest corrections. The differences from Abbe's table are trifling, and mainly confined to two years (1891 and 1892). I judged it best, however, to revise the whole of my arithmetic, so as to employ Wolfer's own most approved figures. In the following remarks S represents Wolfer's value for the sun-spot frequency. The above-mentioned table gives the mean S for each month and for each year.

The magnetic quantity selected for comparison is the mean monthly "range," meaning thereby the difference between the greatest and

* 'Met. Zeitschrift,' May, 1902 p. 195.

least of the twenty-four hourly values in the mean diurnal inequality for the month in question, based on the five *quiet* days selected for the month by the Astronomer Royal. Calling this quantity R for any particular magnetic element, I tentatively assumed

$$R = a + bS \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1),$$

with a and b constants. I grouped together the 11 Januarys, the 11 Februarys, and so on, of the 11-year period, and determined a and b by least squares for each of the resulting 12 groups. There being only 11 years' data, the calculated values doubtless are appreciably affected by quasi-accidental irregularities, but there is so striking a resemblance between the more conspicuous features of the results found for the declination, inclination and horizontal force as to justify the conclusion that the phenomena are *bonâ fide*. Full particulars will be given later. At present it will suffice to record the mean values found for the a and b of the formula for three groups of months —viz. :—

Winter, comprising November to February,
Equinox ,, March, April, September, October, and
Summer ,, May to August.

The results are as follows :—

Table I.

	Declination.		Inclination.		Horizontal force. (Unit $1\gamma \equiv 10^{-5}$ C.G.S.)		Vertical force. (Unit $1\gamma \equiv 10^{-5}$ C.G.S.)	
	a.	*b.*	*a.*	*b.*	*a.*	*b.*	*a.*	*b.*
Winter ...	3′·23	0′·0323	0′·63	0′·0105	10·5	0·161	7·0	0·032
Equinox ..	7 ·32	0 ·0478	1·26	0 ·0147	23·5	0·221	17·2	0·026
Summer ..	8 ·91	0 ·0428	1·61	0 ·0137	30·6	0·190	22·7	0·035
Mean.....	6 ·49	0 ·0410	1·17	0 ·0130	21·5	0·191	15·6	0·031

As is obvious from (1), a represents the amplitude of the range corresponding to a total absence of sun-spots. During the eleven years dealt with, Wolfer's mean monthly values for S varied from 0·3 to 129·2, the mean being 41·7.

To bring out more clearly the similarity of the results for the declination, inclination and horizontal force, I have represented the mean value of b for the 12 months in each element by 100. The corresponding values for the three seasons are, then, as follows :—

Table II.

	Winter.	Equinox.	Summer.
Declination	79	117	104
Inclination	81	113	106
Horizontal force.. ...	85	116	99

In obtaining these figures I have retained a figure in the value of b beyond that recorded in Table I.

Tables I and II will suffice to bring out one of the most important points established, viz., that b is certainly different from one month to another, and is, for all the elements except the vertical force, decidedly larger at the equinoxes (more especially it would appear at the spring equinox) than at other seasons. This means that the equinoxes are the seasons at which the amplitude of the diurnal inequality, when considered *absolutely*, is most dependent on the sun-spot frequency. When we take into account, however, the difference between the ranges of the diurnal inequalities at different seasons of the year, we find that winter is the season when sun-spot frequency is *relatively* most important. This will be recognised on reference to Table III, remembering that a represents the range corresponding to a total absence of sun-spots, while $a + 41{\cdot}7\ b$ is the range corresponding to a sun-spot frequency of 41·7, this being, as already mentioned, Wolfer's mean value for the 11 years in question.

Table III.

Values of $41{\cdot}7b \div a$.

	Declination.	Inclination.	Horizontal force.	Vertical force.
Winter	0·42	0·69	0·60	0·19
Equinox	0·27	0·49	0·39	0·06
Summer	0·20	0·35	0·26	0·07

Table III serves also to bring out another important result, viz., that the influence of sun-spot frequency on the amplitude of the diurnal inequality is very much less for the vertical force than for the three other elements considered.

A recent interesting paper by Rajna* shows that the idea of a linear relationship between diurnal magnetic range and sun-spot frequency has already been applied by at least two previous investigators, Rajna and Wolfer. They seem, however, to have applied it only to mean annual values, and to have considered declination only. Rajna, dealing with declination data, observed at Milan over the long period 1836 to 1901, applies a formula of type (1) to what he calls the "medie annuali dell' escursione diurna."

The value he finds for b is 0′·047. He mentions that in an earlier similar investigation, including declination data from several stations, Wolfer obtained the value 0′·040.

I am uncertain as to the precise meaning of Rajna's "medie annuali," but it certainly is not quite the same thing as the mean range in Table I, so that the results are not absolutely comparable.

* 'Rendiconti del R. Ist. Lomb.,' Serie II, vol. 35 1902.

Another recent and able paper bearing on the subject appears in the last published volume of the French Bureau Météorologique, which has just come into my hands. The author, Mr. Alfred Angot, has anticipated me in applying a formula of type (1) to the individual months of the year; but he treats of the amplitude, not of the diurnal range as a whole, but of that of the coefficients of the several terms of the Fourier's series into which the diurnal inequality can be analysed. The paper treats only of the declination—dealing with data from ordinary days at Parc St.-Maur, Greenwich and Batavia—but the author expresses his intention of considering in the future the horizontal force.

A special feature of the present investigation is that the magnetic data are derived exclusively from magnetic *quiet* days. This suggests at once a query and a criticism, a query as to why one did not employ corresponding sun-spot data confined to the magnetically quiet days, a criticism that as the two sets of data employed do not absolutely correspond, the comparison actually made may be misleading.

As to the query: Wolfer, it is true, publishes at regular intervals in the 'Met. Zeitschrift' *provisional* sun-spot frequencies for each day. These figures are, however, presumably inferior in certainty to the final figures he has embodied in his table after consulting all available sources of information. The vital consideration, however, is that at certain seasons of the year there are a number of days for which, owing to the absence of observations, Wolfer has no provisional sun-spot data. With information lacking for two or three out of the five quiet days of a month there would have been a very undesirable amount of uncertainty. As to the criticism, it would be difficult to meet it if it could be held that the enhanced magnetic activity existing at the earth's surface at times of sun-spot maxima is due directly to electrical disturbances in the sun, each disturbance being limited to regions where sun-spots exist, and only those disturbances being effective which happen to be at the moment on the half of the sun visible from the earth. At present I shall only mention the following fact:—I had monthly sun-spot frequencies calculated from Wolfer's *provisional* figures, employing only the five "quiet" days selected for each month by the Astronomer Royal. The mean sun-spot frequency thence deduced for the eleven years (1890 to 1900) differed from the corresponding result given by all Wolfer's days by less than one-fifth of 1 per cent. It is hardly necessary to point out that this fact has an important bearing, not only on the point immediately under consideration, but also on the further question as to the true nature of the connection between sun-spots and magnetic storms.

"The Relation between Solar Prominences and Terrestrial Magnetism." By Sir NORMAN LOCKYER, K.C.B., F.R.S., and WILLIAM J. S. LOCKYER, M.A., Ph.D., F.R.A.S. Received January 14,—Read January 29, 1903.

(PLATES [1] AND [2].)

It has been stated in a previous communication* that a preliminary reduction of the Roman observations of prominences, observed on the sun's limb by Tacchini, indicated that, in addition to main epochs of maxima and minima of prominences coinciding in time with those of the maxima and minima of the total spotted area, there are also prominent subsidiary maxima and minima.

One of us has pointed out in a recent communication to the Académie des Sciences† that a comparison of the frequency of prominences visible in each solar latitude with the frequency of the most intense magnetic storms, indicated that (*a*) magnetic storms classed as "great" by Ellis, and the greatest prominence activity near the poles of the sun occurred at the same time; and (*b*) that the curve of general magnetic activity was nearly the same as that of the prominences observed near the solar equator.

The object of the present communication is to give a more detailed account of the research so far as it has gone.

The Observations of Prominences.

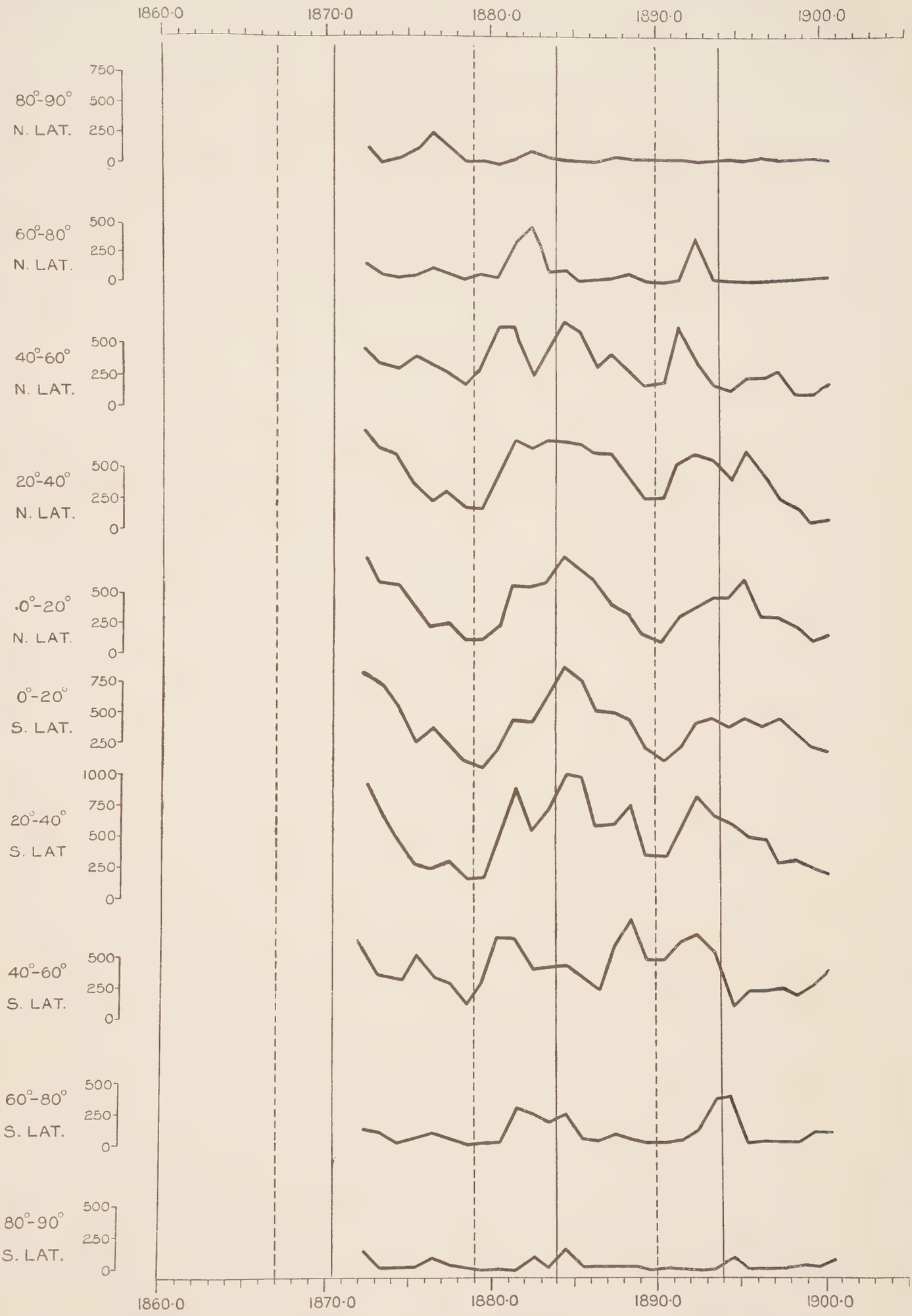
The fine series of observations, made by Tacchini, of the numbers and latitudes of prominences seen on the sun's limb was used as a basis for the curves discussed. These observations were commenced in 1872, and have been continued up to the present day, so that we have a valuable continuous record. They have been published‡ from time to time in full detail, thus rendering it possible to deal with them in any manner that may be desired. In the reduction of the observations each zone of 10° was examined and discussed by itself. The observations were divided in the first instance into groups of three months, and the percentage frequency of the prominences was determined by dividing the number observed by the number of days on which observations were made in this period.

In this way a set of eighteen curves, nine for each hemisphere, was made, showing the variation from year to year of the percentage frequency of prominence activity in each ten-degree zone.

* 'Roy. Soc. Proc.,' vol. 70, p. 502.

† 'Comptes Rendus,' vol. 135, No. 8, 25th August, 1902.

'Società degli Spettroscopisti Italiani,' vol. 1, 1872; vol. 29, 1900.



Curves showing the percentage frequency of solar prominences for each 20° zone N. and S.
(The continuous and broken vertical lines indicate the epochs of sun-spot maxima and minima respectively.)

In the curves accompanying the present communication (Plate [1]) the above-mentioned set, except those for 80°—90° north and south, have been grouped in pairs, thus representing the percentage frequency of prominences in each hemisphere for zones of 20° of latitude, 0°—20°, 20°—40°, &c., since it was found that this reduction could be made without losing any of the characteristic variations.

An examination of these curves shows that they differ very considerably one from the other as we proceed from the equatorial to the polar zones. Generally speaking the curves representing the variations for each of the zones, 0°—20° north and south, conform with the sun-spot curve; that is, the maxima and minima occur at about the epochs of sun-spot maxima and minima. Those for the two zones, 20°—40°, in both hemispheres conform also in the main to the general sun-spot curve, but in addition they display subsidiary maxima or changes of curvature superimposed on the main curve.

The curves for the two zones, 40°—60° north and south, have, on the other hand, hardly any likeness to the sun-spot curve, but are made up of a series of prominent maxima representing special outbursts of prominence activity.

Passing to the curves corresponding to the next zones, *i.e.*, 60°—80° north and south, these indicate two prominent outbursts lasting for a short period, showing that this region of the sun is, as a rule, practically free from prominence activity; in the remaining zones, 80°—90° north and south, the variation is small, and is a faint echo of the condition of affairs in the neighbouring zone 60°—80°.

The Magnetic Curves.

The data regarding the magnetic phenomena employed in this comparison are those brought together by Mr. William Ellis, in two published papers on magnetic phenomena.*

We may take the opportunity here of thanking Mr. Ellis for kindly communicating to us a continuation of the data published in these two papers, which information he has brought down to the year 1899.

Two classes of magnetic phenomena were there dealt with, namely, the variations from year to year of the diurnal range of the declination and horizontal force, and magnetic disturbances.

As regards the former, Mr. Ellis has shown† that the curves indicating these variations are very similar to that of the general sun-spot curve; in fact, the curves were found to be almost identical in all their smaller irregularities.

* 'Phil. Trans.,' Part II, 1880, "On the Relation between the Diurnal Range of Magnetic Declination and Horizontal Force, as observed at the Royal Observatory, Greenwich, during the years 1841 to 1877, and the Period of Solar Spot Frequency"; 'Monthly Notices, R.A.S.,' December, 1899, vol. 60, No. 2, "On the Relation between Magnetic Disturbance and the Period of Solar Spot Frequency."

† 'Phil. Trans.,' Part II, 1880.

The second class of phenomena, namely, the magnetic disturbances; which are more irregular in occurrence, has been classified by Mr. Ellis into five groups, and tabulated by him under five separate subheads. For the present paper, reference will only be made to one of these classes, namely, that described as "great," this group representing the largest disturbances. The curve representing the variation in number of these disturbances indicates short intermittent crests, outbursts, in fact, with rapid rises to maxima and falls to minima, and comparatively long intervals of quiescence.

Comparison of the Curves representing Prominence Frequency and Variation of Diurnal Magnetic Range.

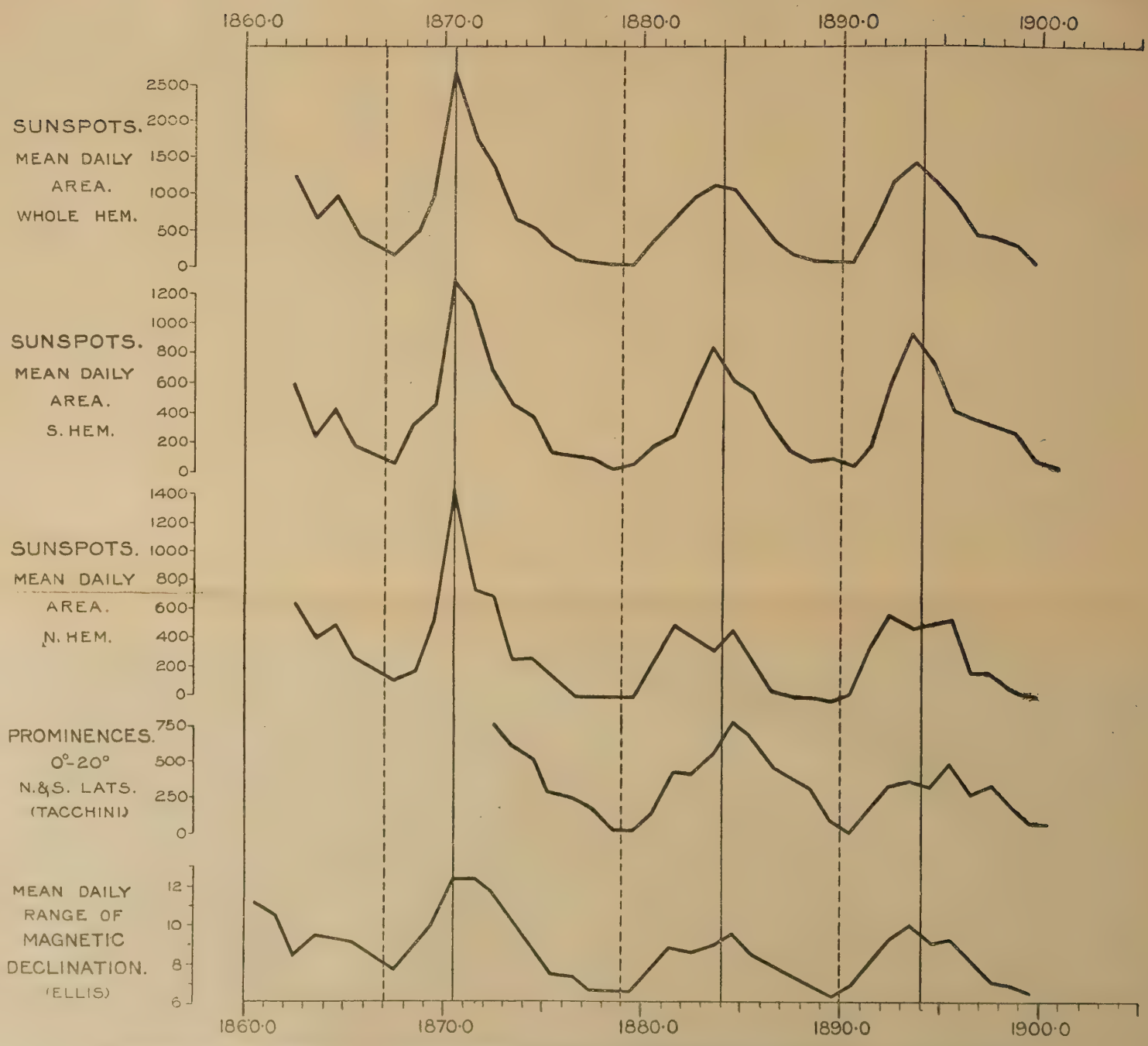
Mr. Ellis, as already has been pointed out, has indicated the close resemblance between the sun-spot curve and that representing the variation of the magnetic elements; and it has been shown in the earlier part of this paper, that the curves representing the percentage frequency of prominences near the solar equator, conform in the main to the general sun-spot curve.

There is therefore an apparent connection between phenomena occurring in the equatorial regions of the sun (as represented by zones of prominences near the equator, and sun-spots which are practically restricted to these zones), and the ordinary diurnal magnetic variation.

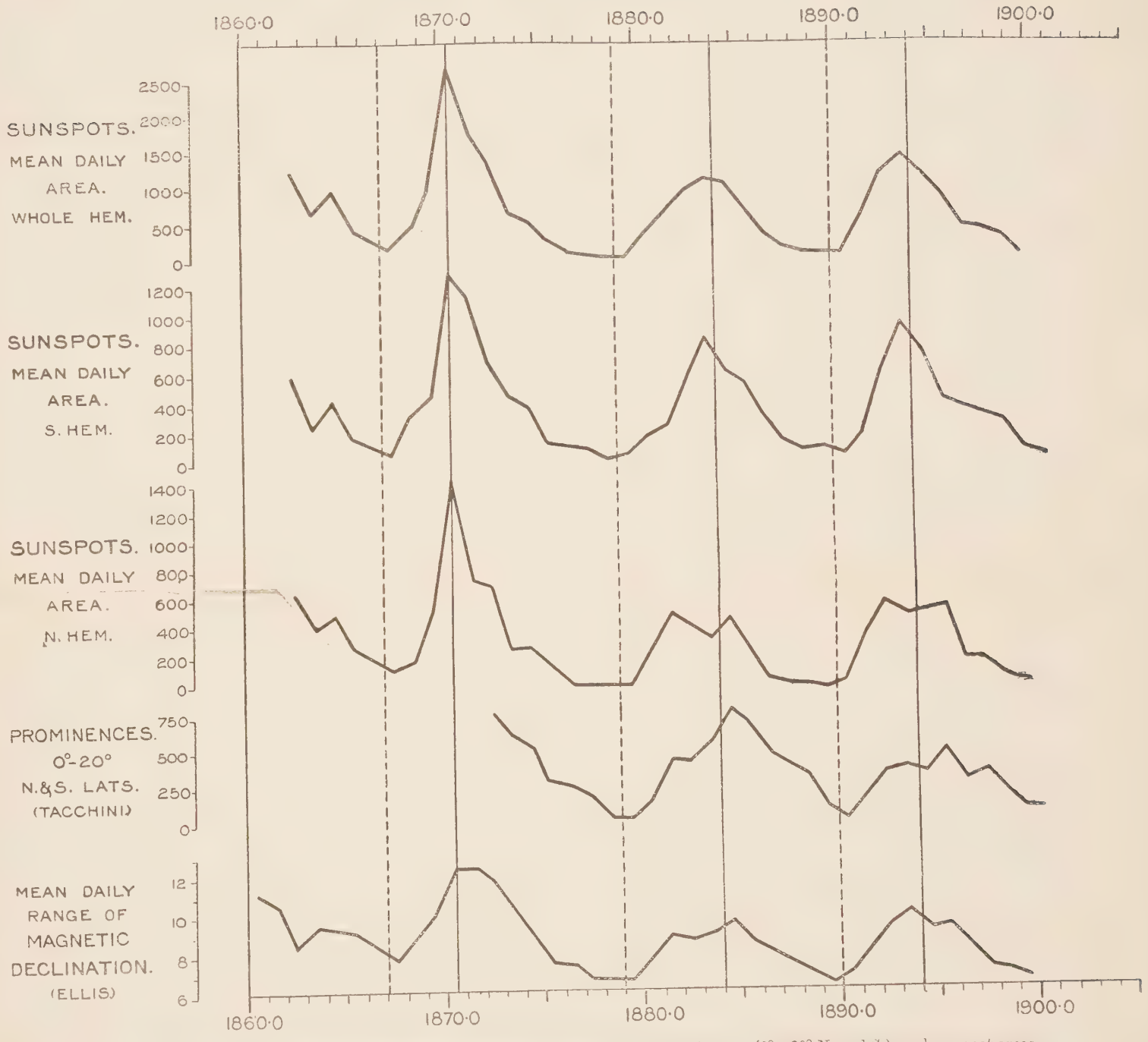
The accompanying set of curves (Plate [2]) illustrates the great similarity between those showing the frequency of prominences in a zone about the equator (0°—20° north and south) and the variations of the mean daily range of magnetic declination; for the sake of comparison, three other curves are added, showing the variation of the mean daily area of sun-spots for the whole, and the two hemispheres of the sun separately.*

* In referring to the curve representing the variation of the mean daily areas of sun-spots, it may be noted that this is obtained by combining the mean daily areas of both hemispheres of the sun. A closer analysis shows, however, that this variation is not the same for both hemispheres. From the year 1862, when such a division of the sun's disc can be easily investigated, the northern hemisphere, about the time of the two last maxima, displayed double maxima occurring in the years 1881 and 1884, and in the years 1892 and 1895. About the time of the maximum of 1870 this duplicity is not so marked, although when compared with the curve for the southern hemisphere for this period, there is a slight indication of a subsidiary crest in 1872. In the case of the curve representing the mean spotted area for the southern hemisphere alone, at all the three epochs of maximum, the curves are single-crested and indicate sharply-defined maxima in the years 1870, 1883, and 1893.

From the above it will be seen, therefore, that the actual epochs of sun-spot maxima, as determined from the northern and southern hemispheres respectively,



Comparison of curves representing variations of magnetic declination, solar prominences (0°—20° N. and S.), and sun-spot areas.
(Continuous and broken vertical lines as in Plate 4.)



Comparison of curves representing variations of magnetic declination, solar prominences (0°—20° N. and S.), and sun-spot areas.
(Continuous and broken vertical lines as in Plate 4.)

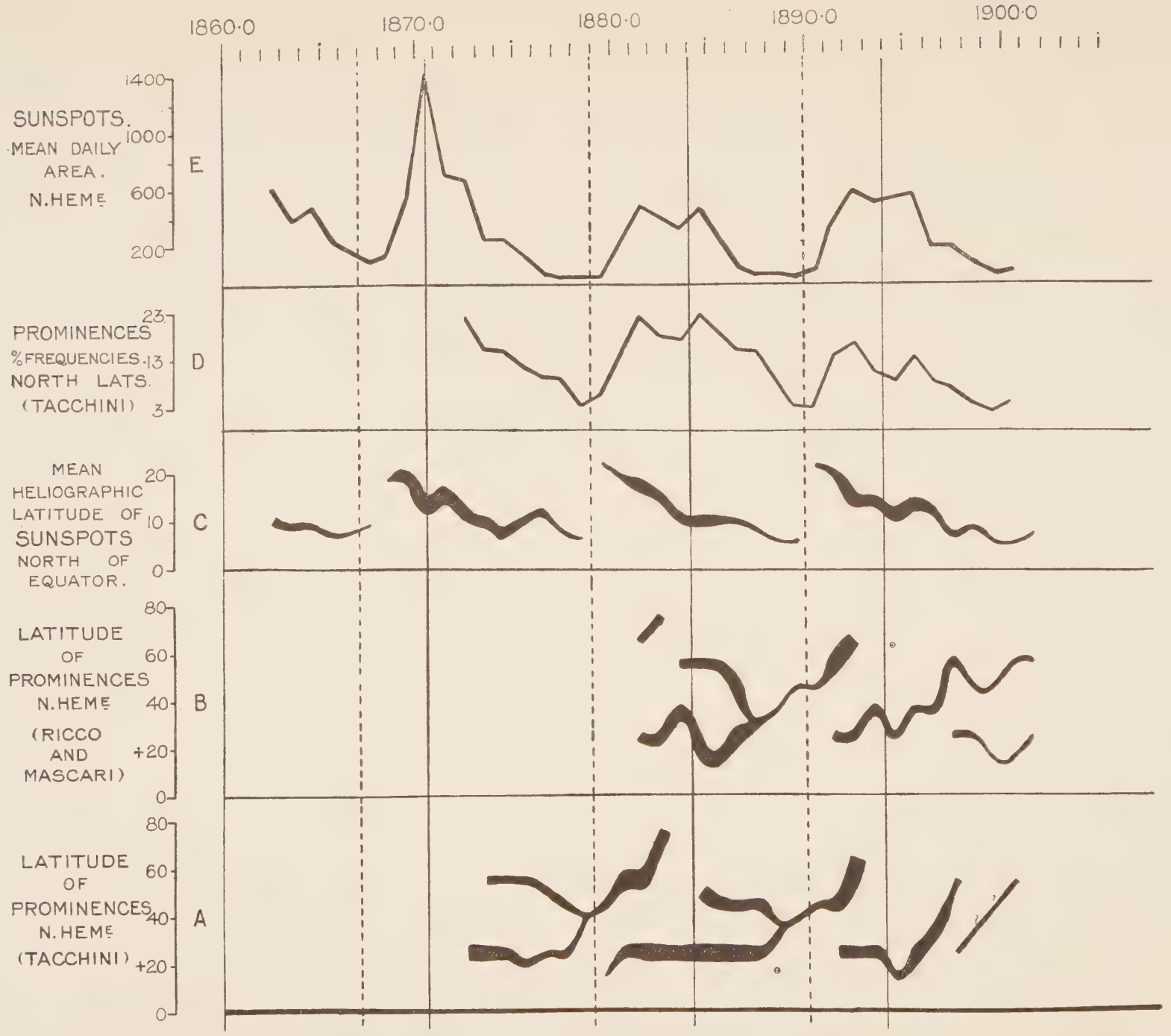


PLATE 6.—Curves showing the Relation between the Positions of the Centres of Action of Solar Prominences (A and B) and Spots (C), Percentage Frequency of Prominences (D), and Mean Daily Areas of Spots (E), for the Northern Hemisphere of the Sun.

Note.—The continuous and broken vertical lines represent the epochs of sunspot maxima and minima as determined from the mean daily areas of the whole solar disk.

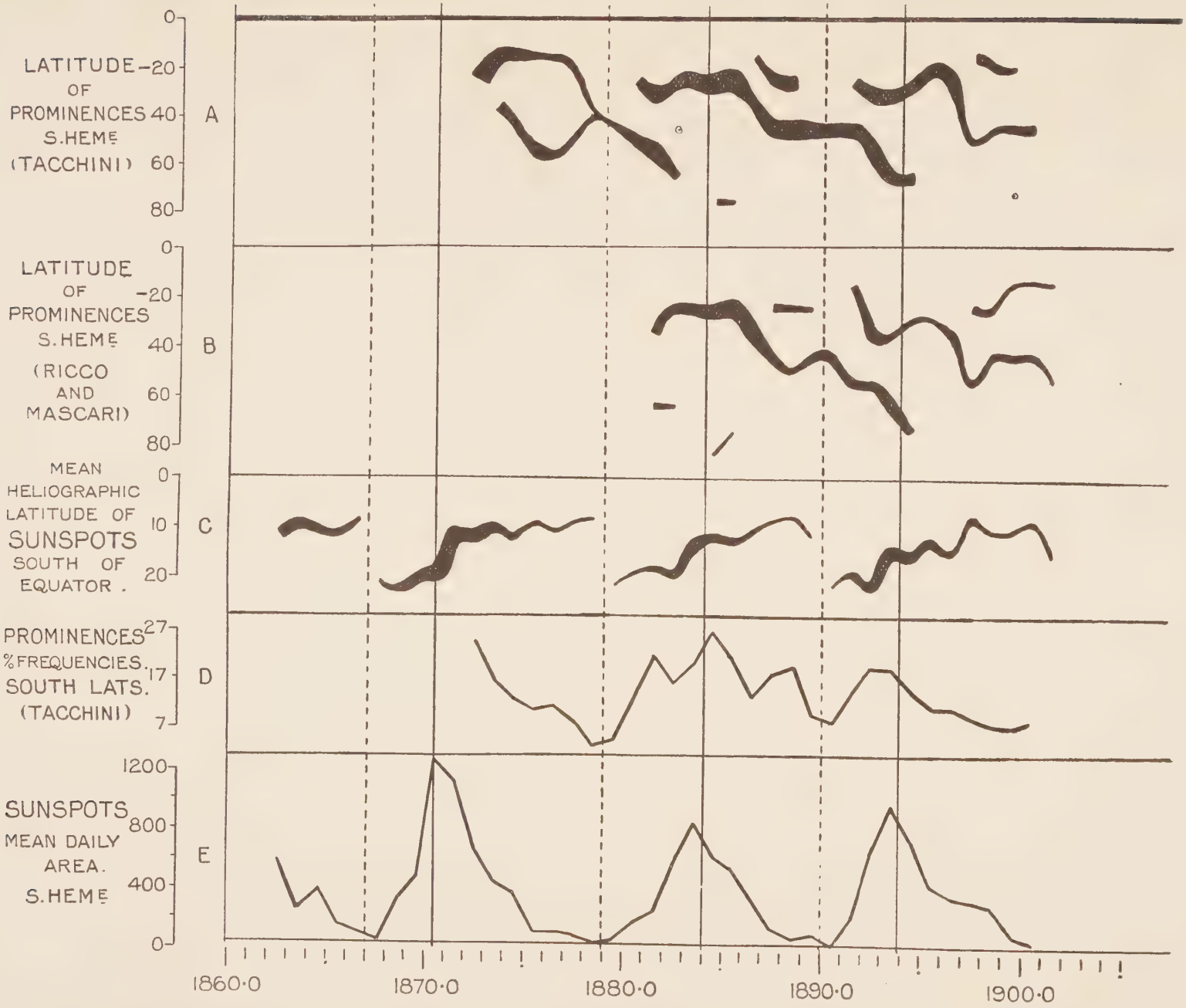


PLATE 7.—Similar Curves to those on Plate 1, only in this case the Southern Hemisphere of the Sun is referred to. Vertical lines same as on Plate 1.

Comparison of the Prominences with the Magnetic Disturbance Curves.

If a comparison of the curve representing the number of days of the "great" magnetic disturbance is made with those representing prominence frequency (Plate [1]), it will be seen that the former is as unlike the curves representing the prominence frequency about the solar equator as it is like those near the poles; in fact, the polar prominence outbursts, and great magnetic disturbances occur almost simultaneously.

The peculiar form and general similarity of the curves can be best seen from the accompanying illustration (fig. 1). In the figure comparison is made between the epochs of the crossing of the known and unknown lines, the percentage frequency of prominences about the solar poles and Ellis' "great" magnetic disturbances.

Two curves representative of prominence frequency are given, one to indicate the abrupt nature of the curves representing the frequency in a zone near the pole 10 degrees in width (in this case 60°—70° north), and the second to illustrate polar action as a whole; this latter was obtained by making a summation of prominence frequency for the two zones 60°—90° north and south.

The simultaneous occurrence of the maxima suggests that, when the prominence action takes place at the polar regions of the sun, one effect on the earth is that we experience our greatest magnetic disturbances.

Further, according to Mr. Ellis,* "unusual magnetic disturbance is frequent about epochs of sun-spot maximum, and nearly or quite absent about epochs of sun-spot minimum."

We find that not only do these "great" disturbances occur at the same time as the polar prominences, but the spectroscopic observations of sun-spots show that they take place not only "about" the times of spot maximum, as stated by Mr. Ellis, but when the sun-spot curve is *approaching* a maximum and at the dates of the widened line crossings,† when the curve representing the "unknown" lines is on the rise, and crosses the "known" line which is descending. At the other epoch of "crossing," *i.e.*, when the curve showing the "known" lines is on the rise and the "unknown" is falling, there is practically no magnetic disturbance recorded. Attention is again drawn to these crossings, as it is desired to indicate that it is only at those particular times when the sun is increasing his temperature that these disturbances occur.

are not the same, and in dealing with the curve representing this variation for the whole hemisphere, this fact should be borne in mind.

It may further be noted that the epochs of minima may be practically considered the same for both hemispheres.

* 'Monthly Notices R.A.S.,' vol. 60, p. 148.

† 'Roy. Soc. Proc.,' vol. 67, p. 412.

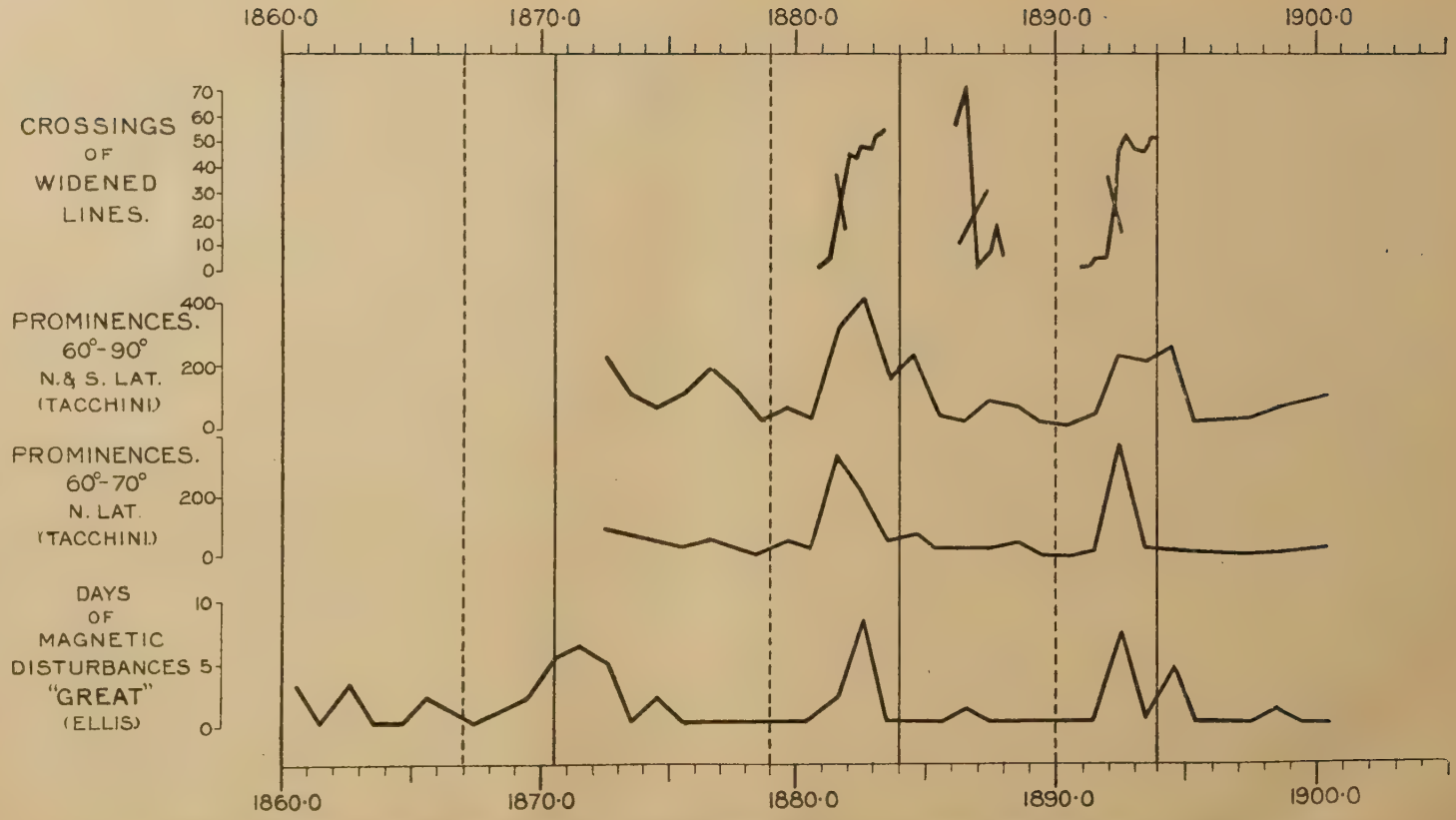


FIG. 1.—Comparison showing days of "great" magnetic disturbance, polar prominences, and crossings of widened lines. (The continuous and broken vertical lines indicate the epochs of sun-spot maxima and minima respectively.)

The facts in this paper explain why it is that magnetic storms sometimes take place when there are no spots, or no very large spots, on the surface of the sun. Since the occurrence of magnetic storms is

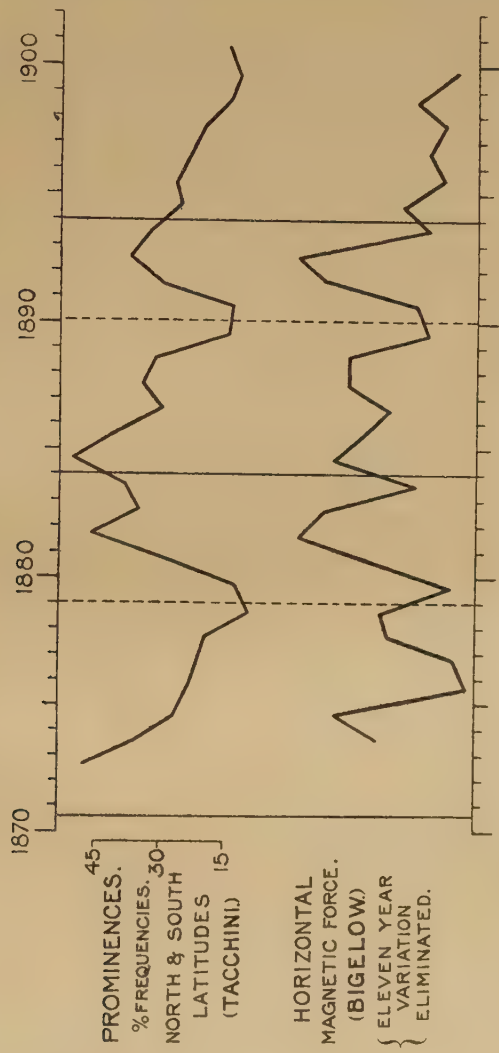


FIG. 2.—Comparison between horizontal magnetic force (Bigelow) and solar prominences (Tacchini). (Continuous and broken vertical lines as in fig. 1.)

shown to be very closely connected with the solar prominences, there may be prominences and magnetic storms when there are no spots. Prominences may also sometimes be associated with large spots, and as the latter can be seen while the former can not, the resulting magnetic storm is generally attributed to the spots.

Further, the magnitude of magnetic storms appears to vary according to the particular position as to latitude of the prominence on the sun's disc. The nearer the poles (either north or south) the prominence occurs, the greater the magnetic storm, and these are the regions where no spots exist.

In this paper we have shown that the variations of the general magnetic phenomena, as given by Ellis, synchronise with the occurrence of prominences about the solar equator, while his "great" magnetic disturbances occur, in point of time, with the appearance of prominences in the polar regions of the sun.

Professor Bigelow has recently* investigated the variations in the horizontal magnetic force, and finds that the curve representing these changes exhibits subsidiary maxima which synchronise with those recorded in the curve representing the mean variation of prominences for all latitudes. Thus, to use his own words, "the remarkable synchronism between the curves cannot escape recognition, except after the year 1894, when an extra minor crest is developed in the horizontal force."

The accompanying diagram (fig. 2) gives Professor Bigelow's curve, which represents, as he says, "the series of minor variations which were found in the horizontal magnetic force . . . . after the 11-year cycle curve has been eliminated," together with the percentage frequency of prominences in all latitudes obtained by us from Tacchini's observations.

* 'Monthly Weather Review,' vol. 30, No. 7, July, 1902, p. 352.

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Sir Norman Lockyer and Dr. W. J. S. Lockyer, Solar prominence and spot circulation, 1872—1901 . . . . . [14]

"Solar Prominence and Spot Circulation, 1872—1901." By Sir Norman Lockyer, K.C.B., F.R.S., and William J. S. Lockyer, Chief Assistant, Solar Physics Observatory, M.A. (Camb.), Ph.D. (Gött.), F.R.A.S. Received March 17,—Read March 26, 1903.

(Plates [3] and [4].)

In our former communications* referring to the connection between solar, meteorological, and magnetic changes, some of the results obtained by the reduction of the solar prominences, as observed by Professor Tacchini at Rome, were described. It was stated that the curve representing the variation of percentage frequency of the prominences for the whole limb of the sun indicated that in addition to the main epochs of maxima and minima coinciding in time generally with those of the maxima and minima of the total spotted area, there were also prominent subsidiary maxima and minima.

Further, dividing the sun's limb into zones of 20° in width from the equator, with a polar zone of 10°, and discussing each zone separately, the variation of the prominence percentage frequency about the equator was found to be very different from that in the higher latitudes, the former changing with the spots, and the latter exhibiting sudden outbursts just previous to the epochs of sunspot maxima, followed and preceded by comparatively long intervals of quietude.

In the present communication, the prominence observations have been discussed from a different point of view, in order to trace out, if possible, the heliographic latitudes of the chief centres of action of prominence disturbance. In this way it could be determined whether such movements are subject to some periodic law, in which case it would be possible to increase our knowledge of the circulation of the solar atmosphere in regions outside those in which sunspots alone have, up to the present, been employed.

The changes of latitude of the zones which contain the centres of sunspot disturbances were first pointed out by Carrington,† whose fine series of observations led him to discover "a greater contraction of the limiting parallels between which spots were formed for the two years previous to the minimum of 1856, and soon after this epoch the apparent commencement of two fresh belts of spots in higher latitudes north and south, which have in subsequent years shown a tendency to coalesce, and ultimately to contract as before to extinction."

The study of the subject was taken up later by Spoerer,‡ who

* 'Roy. Soc. Proc.,' vol. 70, p. 502; vol. 71, pp. 134 and 244.

† 'Observations of the Spots on the Sun from November 9, 1853, to March 24, 1861, made at Redhill,' p. 17.

‡ 'Beobachtungen der Sonnenflecken von Oct., 1871—Dec., 1873, und von Jan.,

corroborated Carrington's results and extended the discussion of the observations up to the end of the year 1879.

The result of these two investigations showed that at sunspot maximum there was only one zone in each hemisphere in which spots were situated, the centre of this being about 18° N and S, while at minimum there were two zones existing simultaneously in each hemisphere; the older cycle dying out in the zone, the centre of which was situated in low latitudes, and the new one commencing in high latitudes, its centre being about latitude $\pm 30°$ to $\pm 35°$.

Later observations extending up to the present year have further corroborated these general deductions, for each hemisphere, and we are now quite familiar with this cycle of sunspot latitude variation.

In the present investigation, the fact has been brought out that the prominences also undergo an apparently regular variation of latitude throughout a period of about eleven years concurrently with the spots.

For the purpose of our inquiry, the object of which has been stated above, we have discussed independently of each other, two fine series of prominence observations, one made by Tacchini at Rome extending from 1872 to 1900, and the other by Ricco and Mascari at Catania from 1881 to 1901.

Both these series were handled in the same way, and both indicated similar changes of latitude of prominence action, showing that the variations recorded were real and not due to any personality of the observer or difference in the method of observation.

The data for the discussion of the solar prominences as observed by Tacchini have been taken from the same source as before,* while those of Ricco and Mascari are published in and have been extracted from the same volumes.

We may here take the opportunity to express our thanks to Professor Ricco, with whom we have been in communication, and who has very kindly forwarded for our use some unpublished data concerning his prominence observations and reductions.

The method of reduction adopted was to determine for each year the percentage frequency of prominence activity for every 10 degrees of solar latitude north and south. A series of curves was next drawn, one for each year, the abscissæ representing the latitudes of prominences north and south, and the ordinates their percentage frequency. It was then found that the centres of prominence activity, or, in other words, the maxima of the curves, were sometimes single, sometimes double, and in one or two cases even triple in each hemisphere. This suggested that just as sometimes there are two

1874—Dec., 1879.' 'Publicationen des Astrophysikalischen Observatoriums zu Potsdam,' Band I and II.

* 'Società Spettroscopisti Italiani, vol. 1, 1872, to vol. 29, 1900.

zones of spots existing at one time, so there might be one, two, or occasionally three zones of prominences in existence in each hemisphere simultaneously.

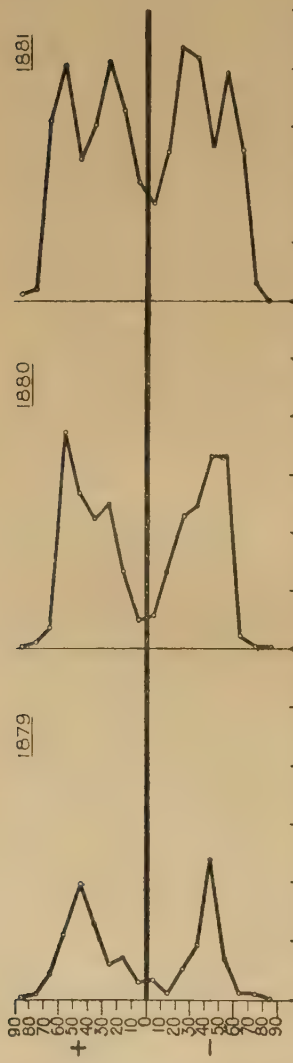

Fig. 1.—Curves showing the variation of the percentage frequency of prominence activity for every 10° of latitude for the years 1879—1881, from Tacchini's observations.

Further, a close examination of the whole set of curves with reference to these points of maxima made it possible not only to study the changes of latitude of these points from year to year and their positions when commencing to develop or about to disappear, but the intensity of these centres in relation to each other.

The accompanying illustration (fig. 1) shows the curves drawn for the years 1879, 1880, and 1881, from the observations of Tacchini, and serves as an example of the curves that have been discussed; they exhibit the change from a single to a double centre of activity in each hemisphere.

Thus in 1879, there was a prominence maximum in each hemisphere at latitudes $\pm 50°$. In the next year (1880), both the maxima had retreated further away from the equator, namely to latitudes $\pm 60°$, while another centre of disturbance began to make itself apparent at latitudes $\pm 30°$. In the year 1881, both centres in each hemisphere were strongly marked and became of about the same intensity, their mean latitudes in each hemisphere being about $\pm 30°$ and $\pm 60°$. These curves thus indicate that during these three years, the direction of motion of these centres of activity tends polewards or away from the equator.

By examining both series of observations made by Tacchini and Ricco and Mascari, and analysing the positions of the principal and

subsidiary maxima for the whole period covered by the observations, the results illustrated graphically in Plates [3] and [4] were obtained.

In these figures the facts are brought together for each hemisphere separately. The medials of the lines (curves A and B) show the heliographic latitudes of the centres of prominence action; the thickness of these lines represents the relative percentage frequency of prominence action.

For the sake of comparison, three other curves for each hemisphere are given. The first (curve C) shows the mean heliographic latitude of spotted area for each hemisphere. For the construction of these, the values, since 1873, have been extracted from the Greenwich Reductions,* but previous to that date the values have been obtained from Mr. Marth's reductions,† and those completed at the Solar Physics Observatory from measures supplied by Professor Backlund, of the Wilna Observatory.

The next curve (curve D) illustrates the variations of the percentage frequency of prominence action for each hemisphere taken, as a whole, and is similar to those given in our former papers.

The last curve (curve E) shows the variation of the mean daily area of sunspots from year to year, also for each hemisphere.

Referring now to the changes of latitude of the prominence centres of activity, both series of curves for the north as well as for the south hemisphere exhibit the same general features.

The first conclusion illustrated by the curves is that prominence activity in the main has a poleward drift, that is, the change of position of the zones of activity is in the direction from low to high latitudes. In some years, the centres of activity appear to form two zones in each hemisphere at about latitudes $\pm$ 24° and $\pm$ 50°, which eventually amalgamate at about latitude $\pm$ 40° and move polewards, fading out in about $\pm$ 70° to $\pm$ 80°. As this zone disappears in high latitudes a new zone at about latitude $\pm$ 20 begins, and this after a few years becomes associated with another zone in about latitude $\pm$ 50°, and eventually amalgamates with it.

The epochs at which these different zones come into play in relation to the general curve of prominence activity for the whole hemisphere are as follows: From a little after the maximum of prominence activity to just before the minimum, two zones in the latitudes $\pm$ 24 and $\pm$ 50° are in existence and of decreasing intensity. Before the minimum is reached these two zones amalgamate in about latitude $\pm$ 40°. At the minimum there is only one zone, and this of small intensity. Between the minimum and the following maximum this zone rapidly takes a northern movement, increasing in intensity; a new outburst

* 'Spectroscopic and Photographic Observations made at Royal Observatory, Greenwich, 1884,' and after.

† MSS. at Royal Society.

occurs in a zone nearer the equator (latitude ± 24°), which also increases rapidly in intensity.

After these general statements, we now refer to some details showing that there are some variations from the above generalisation.

For these details the curves deduced from both sets of observations made by the different observers are so very similar that it does not matter which are examined.

Attention may first be drawn to certain differences between the curves representing the latitude variation for the two hemispheres. It will be noticed that for the period 1872—1882, the curves for both hemispheres are very similar. We next consider the period 1880—1893. Here there are differences between the two hemispheres. The curve for the northern hemisphere resembles very closely that for the preceding period, but it differs somewhat from its corresponding curve for the southern hemisphere. The corresponding northern zone in latitude 45° is missing from the southern hemisphere, while a zone of activity nearer the equator about latitude 24° is present. Further, the polar zone for the southern hemisphere continues to be prominent for two years longer than that in the opposite hemisphere.

In the succeeding curves, which extend from 1891—1901, both hemispheres are more or less similar, and both resemble in a greater degree those for the southern hemisphere for the period 1880–1893 than those for the period 1872—1882.

Although the Roman and Sicilian observations give nearly identical curves, hemisphere for hemisphere, the apparently regular cycle of change of latitude which was operative for the northern hemisphere 1872—1893, and for the southern hemisphere 1872—1882, does not seem to have been so exactly maintained in late years; more irregular still perhaps is the last cycle commencing in the year 1892. Hence, there seems reason to believe that the prominence circulation is not quite the same for each cycle, and this may in some way be due to a longer solar period such as that of about 35 years.

But it is important to state that our deductions may be partially incomplete owing to the difficulty of determining sometimes whether a new centre of action has been formed or the position of an old one changed. Further, account must be taken of the fact that the material discussed does not represent the record of the percentage frequency of prominences determined from observations made on the disc of the sun (now rendered possible by the Janssen-Hale-Deslandres method), but one obtained from observations of the phenomena occurring only at the limb of the sun. The close agreement between the observation of the different observers shows nevertheless that this latter method is of great value.

Another important series of prominence observations is that made

by Father A. Fényi, S.J., who has published* the individual observations, and the reductions of the positions and frequency of prominences observed at Haynald Observatory for the years 1884 to 1890 inclusive. He gives curves constructed somewhat after the manner adopted in the present inquiry, as illustrated above, in fig. 1. A comparison of the points of maxima from his curves with those of Tacchini and Ricco and Mascari for the period common to all three sets of observations is made in the following tables, each hemisphere being given separately. The vertical columns show, for each year, the heliographic latitudes of the points of maxima, and an asterisk (*) is placed against the one which is the more or most prominent in each hemisphere; when there are two, and they are of equal intensity, this symbol is attached to each, while in the case of only slight indications of maxima the latitude is inclosed in brackets.

Northern Hemisphere.

	1884.	1885.	1886.	1887.	1888.	1889.	1890.
Tacchini	50, 25*	45, 25*	45, 20*	35	35*, 15	40	45
Ricco and Mascari	55, 20*	55, 15*	45, 25*	30	35	45	45
Fényi	65, 45, 15*	45, 25*	45, 20*	45	40*, 20	43*, 25	45

Southern Hemisphere.

	1884.	1885.	1886.	1887.	1888.	1889.	1890.
Tacchini ..	(75), 25*, 5	25	35, 20*	45*, 25	45*, 25	45	45
Ricco and Mascari	(85), 25*, (5)	25	35	45*, 25	50*, 25*	45	50
Fényi	(75), 35*, 15*	(50), 35, 10*	35*, 10*	50*, 30, 15	50*, 25	40	50*, 20

It will be seen that for these seven years, Fényi's results are in very close accordance with those deduced from the other two series of observations, thus generally endorsing those portions of the curves in Plates [3] and [4] covering this period.

It was mentioned in a previous paper† that the mean prominence curve for each hemisphere exhibited subsidiary maxima and minima. In the light of the present investigation, it is interesting to compare

* 'Publicationen des Haynald-Observatoriums, Kalocsa,' Heft VI, 1892, und VIII, 1902.

† 'Roy. Soc. Proc.,' vol. 71, p. 244.

this curve with that representing the changes of latitude of the zones of prominences. In every case, and for each hemisphere, the subsidiary maxima are coincident in time with the presence of two zones of prominences, each well-developed, while at the principal minima only one zone is in evidence.

We have already explained the fact that spots are restricted to a zone having its limits at latitudes ± 5° and ± 35°, while prominences occur all over the sun's disc, even up to the poles, and also that spots always commence their cycle in high latitudes (about ± 35°) and gradually approach the equator until within 5°, when a new cycle is commenced in high latitudes. Prominences on the other hand begin in comparatively low latitudes (about ± 24°), and finish their cycle near the poles.

A glance at the Plates [3] and [4] brings out the interesting fact that at sunspot minima, when two zones of spots are in evidence, there is only one zone of prominences, while when only one zone of spots exists the prominences are for the most part confined to two zones.

The conclusions arrived at in the present communication may be summarised as follows:—

1. The centres of action of prominence activity undergo an apparently regular variation.

2. The direction of motion of these centres is from low to high latitudes, the reverse of that of spots, which travel from high to low latitudes.

3. At epochs of prominence minima (which are concurrent with sunspot minima) these centres of action are restricted to one zone (about latitude ± 44°) in each hemisphere, while those of the spots occupy two zones in each hemisphere.

4. At nearly all other times these centres are apparent in two zones while those of the spots occupy only one in each hemisphere.

5. The subsidiary maxima exhibited by the curves representing the percentage frequency of prominence activity for each entire hemisphere, are due to the presence of two well-developed centres of prominence activity in each hemisphere.

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